TEXT BOOKS FOR

Electrical Engineering Students

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TECHNICAL ELECTRICITY. [illegible] M.I.E.I., and H. W. [illegible] *Fourth Edition.*

CONTINUOUS CURRENT [illegible] By W. T[illegible] M[illegible] *Second Edition.*

ALTERNATING CURRENT [illegible] By W. T[illegible] M[illegible]

ADVANCED TEXT BOOK [illegible] TRICITY. By H. W. H[illegible] Two Volumes. *Second Edition.*

A TEXT-BOOK OF WIRELESS TELEGRAPHY AND TELEPHONY

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A TEXT-BOOK OF

WIRELESS TELEGRAPHY AND TELEPHONY

BY

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PREFACE.

Although a large number of books dealing with Wireless Telegraphy and Wireless Telephony have already been published, especially during the last few years, there is one class of reader that appears to have been rather neglected, namely the person who has been trained, or is being trained, as an electrical engineer, and who possesses knowledge of the fundamental principles of Electrical Engineering but is not an expert wireless engineer. To this class might perhaps be added the Physics student or general reader equipped with a sound knowledge of the elements of Magnetism and Electricity.

Too often published matter on Wireless Telegraphy and Telephony, both books and articles, is intended for the amateur with little or no knowledge of the principles of Electrical Engineering, or it goes to the other extreme and caters only for the needs of the specialist in Wireless Telegraphy and Telephony. The average electrical engineer or student of Electricity and Electrical Engineering derives very little benefit from reading either type of publication, and the slight increase in knowledge he may acquire involves much waste of time and energy in reading matter with which he is already familiar or with which he is not concerned at the moment.

The object of this book is, therefore, to attempt to fill the gap, and to treat the subject of Wireless Telegraphy and Telephony as a branch of Electrical Engineering in much the

same way as the generation, transmission, and distribution of electrical energy, the design of electrical machinery, and other electrical subjects are treated for the average electrical student.

The book is not intended to meet the needs of the specialist, but it is hoped that even experienced wireless engineers, as well as potential wireless engineers, will find it useful.

A knowledge of the fundamentals of Magnetism and Electricity and of Electrical Engineering has been assumed, and the reader equipped with this knowledge will readily follow the subject-matter of the book. For the appreciation of the sections dealing with the mathematical aspects of the subject, a standard of Mathematics about equal to that of the Intermediate B.Sc. (Engineering) examination will be necessary: a knowledge of Mathematics more than that required for this examination has been assumed in certain cases, but in such cases alternative explanations have been given where they have been considered desirable. Further, for the benefit of the less mathematically inclined, the full treatment of these more difficult mathematical problems has been confined to the last chapter, the essential points only being summarised in the earlier chapters.

Each chapter has been made as up-to-date as possible without going too deeply into details, and numerous references to published papers have been given where it was considered likely that more detailed information might be required.

Detailed descriptions of apparatus have not been included as a general rule, for they are available in many text-books, and, usually, are not required by the average electrical engineer or student, who is generally either not greatly concerned with intricate details of apparatus or already quite familiar with them as a result of experience.

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CONTENTS

WIRELESS TELEGRAPHY AND TELEPHONY.

CHAPTER I.

OSCILLATORY CIRCUITS.

1. Introduction: Revision of some Facts about Alternating Currents.—The principles involved in oscillatory circuits, as used in wireless telegraphy and telephony, are essentially the same as those of ordinary alternating current circuits familiar to electrical engineers and electrical engineering students, and for this reason a consideration of oscillatory circuits is included in the first chapter of this book. Before proceeding with this, however, a brief revision of one or two fundamental principles, mainly in connection with alternating currents, is desirable.

The first two important quantities (and units) encountered in the study of continuous current electricity are those of **current strength** and **pressure,** i.e. *potential difference* or *electro-motive force.*

The practical unit of current strength is the **ampere,** usually defined as *that current which, flowing through a solution of silver nitrate, deposits silver at the rate of* ·001118 *gramme per second.* The practical unit of pressure is the **volt,** defined as *that pressure which must exist between two points in order that the energy transformed may be one joule* (10^7 *ergs*) *when one ampere flows for one second.* The quantity of electricity conveyed by one ampere in one second is the **coulomb.**

An alternating current, as the name suggests, flows first in one direction and then in the opposite direction: it rises to a maximum, then dies away to zero, is then reversed, rises to a maximum, then dies away to zero, and so on: the pressure in such a circuit is, of course, also alternating.

If now at any particular moment the alternating pressure, say, has a certain value, and is just going to commence a certain set of variations, then the time which elapses between this instant and the moment when the pressure has the same value, and is just going to commence an identical set of variations, is called the **period**; the number of periods accomplished in one second is the **frequency** (f), and the maximum value of the pressure is called the **amplitude.** Thus in Fig. 1 (a) (in which time is measured along OX, and pressure along OY), the curve shows the variation of voltage with time; the time interval, represented by T′T″ (also AD and BE), is the period: the number of such time intervals as T′T″ in one second is the frequency; and the volts corresponding to the maximum points A, C, D give the amplitude. In most cases in practice the curve shown in Fig. 1 (a) may be taken to be a sine curve.

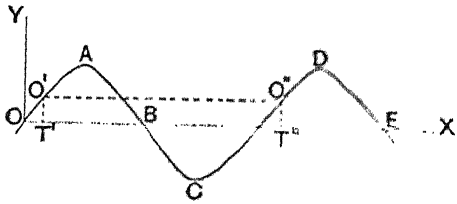


Fig. 1 (a).

The current accompanying the above alternating pressure is also alternating with the same frequency, but in most cases in practice it does not exactly keep in step with the pressure. If the circuit is inductive (see below) the current reaches its maximum, for example, *after* the pressure has reached its maximum, in which case the current is said to **lag.** If the circuit contains capacity (see below) the current reaches its maximum *before* the pressure does, in which case it is said to **lead.** The lag and lead are spoken of as the **phase difference.**

The lag and lead are frequently expressed in terms of the period. Thus, if the maximum current occurred $\frac{1}{8}$ of a period after the maximum E.M.F., the E.M.F. and current would be said to differ in phase by $\frac{1}{8}$ of a period. Taking a complete cycle (*e.g.* BCDE, Fig. 1(a)) as 360°, then (since

angle turned through is proportional to time) the E.M.F. and current would also be said to differ in phase by 60°. If the frequency were 50 cycles per second, the lag could also be said to be $\frac{1}{6}$ of $\frac{1}{50}$, *i.e.* $\frac{1}{300}$ second.

In the measurement of alternating currents the chemical effect mentioned above as a measure of continuous currents cannot be utilised, as the action of the current when flowing in one direction is undone by the reverse current immediately following. On the other hand, a wire is heated by a current independently of its direction, and thus the heating effect can be used for the purpose. For practical purposes of alternating current and pressure measurement, therefore, we use what is called a **virtual ampere,** defined as *that current which will produce the same heat in a conductor as a steady current of one ampere will produce in the same time,* and a **virtual volt,** defined as *that pressure which when applied to the ends of a conductor results in the same heating effect as in the case of a steady pressure of one volt applied for the same time.* Virtual values are often referred to as "the square root of the mean square," or "root mean square," or "R.M.S." values. Further, it can be shown that the virtual value of an alternating current or pressure is ·707 of the maximum value.

In the study of both continuous and alternating currents we must know three things about the *circuit* itself (*i.e.* the path conveying the current) in order to make calculations about current production in it, viz. its **resistance, inductance,** and **capacity.**

The unit of resistance is the **ohm,** defined as *the resistance of a column of mercury* 106·3 *cm. long,* 1 *sq. mm. in cross-section, at the temperature of melting ice.* The unit of inductance is the **henry,** which may be briefly defined as *the inductance of a circuit when current increasing in it at the rate of one ampere per second produces an opposing pressure of one volt.* Finally, the unit of capacity is the **farad,** defined as *the capacity of a condenser which requires a charge of one coulomb of electricity to raise its pressure by one volt.*

The fundamental law for continuous currents (Ohm's law) may be written:—

$$\text{Current (amperes)} = \frac{\text{Pressure (volts)}}{\text{Resistance (ohms)}},\ i.e.\ I = \frac{E}{R} \ldots (1)$$

The corresponding law for alternating currents is:—

$$\text{Current (virtual amperes)} = \frac{\text{Pressure (virtual volts)}}{\text{Impedance}} \quad \ldots(2)$$

In the case of **a circuit with resistance and inductance,** but no capacity, we have:—

$$\text{Impedance} = \sqrt{(\text{Resistance})^2 + (\text{Reactance})^2} \ldots\ldots (3)$$

$$\text{Reactance} = 2\pi f\text{L} = \omega\text{L},$$

where f = frequency, L = inductance in henries, and $\omega = 2\pi f$: if I, E, and R be the virtual amperes, virtual volts, and ohms respectively, we therefore have the formula:—

$$\text{I} = \frac{\text{E}}{\sqrt{\text{R}^2 + (2\pi f\text{L})^2}} = \frac{\text{E}}{\sqrt{\text{R}^2 + \omega^2\text{L}^2}} \quad \ldots\ldots\ldots \quad (4)$$

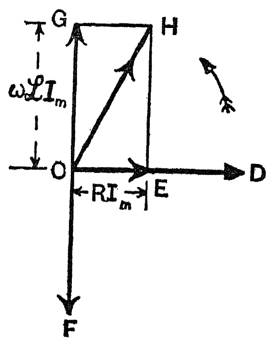
and the current **lags** behind the pressure by an angle whose tangent is measured by Reactance/Resistance: hence, if θ = angle of lag:—

$$\tan \theta = \frac{\omega\text{L}}{\text{R}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

If R be negligibly small compared with L, this expression for the tangent of the angle of lag becomes practically infinite, and the angle of lag therefore 90°: in this case $\text{I} = \frac{\text{E}}{\omega\text{L}}$, and $\text{E} = \omega\text{LI}$.

If two separate continuous pressures E_1 and E_2 are applied to a conductor, the resultant pressure is their sum $(\text{E}_1 + \text{E}_2)$, or their difference, say $(\text{E}_1 - \text{E}_2)$, according as they act in the same or in opposite directions. If two alternating pressures (same frequency) *differing in phase by θ°* be applied to a conductor, the resultant of the two pressures is found by the parallelogram law. Thus, imagine OA and OB to be drawn from a point O, representing say, the maximum values of the two pressures, the angle AOB being θ, then the diagonal OC of the parallelogram AOBC (*i.e.* the parallelogram with OA and OB as adjacent sides) will represent the resultant maximum pressure, and the angle COA will, forexample, represent the phase difference between the resultant and OA. Such a diagram is called a **vector diagram.**

Consider now the vector diagram in the case of a circuit consisting of an *inductionless* resistance (R) in series with an inductance (L) *of negligible resistance*, and an alternating current flowing in the circuit. Let OD (Fig. 1 (*b*)) be the current vector. Then OE, drawn in the same direction and equal to IR, will represent the resistance potential difference. The self-induced E.M.F. in the inductance is represented by OF $= \omega$LI, *a right angle behind* OD, and the potential difference to balance this is represented by OG, equal in magnitude to OF, but in the opposite direction. Completing the rectangle, the diagonal OH is the vector for the resultant potential difference. The angle HOE $= \theta$, for tan HOE $= \frac{\omega L}{R} = \tan\theta$.



VECTOR DIAGRAM.
Fig. 1 (*b*).

In the case of **a circuit with resistance and capacity,** but no inductance, the impedance is $\sqrt{R^2 + \left(\frac{1}{\omega C}\right)^2}$, where C is the capacity in farads, and the law becomes :—

$$I = \frac{E}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

and the current **leads** the pressure by an angle whose tangent is $\frac{1}{\omega C}\Big/R = \frac{1}{\omega CR}$. If R be negligible, the lead becomes 90°, as indicated in the case of the lag above, $I = E\omega C$ and $E = \frac{I}{\omega C}$.

If **the circuit contains resistance, inductance, and capacity,** the law becomes :—

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \quad \ldots\ldots\ldots\ldots (7)$$

and the lag is the angle whose tangent is $\left(\omega L - \frac{1}{\omega C}\right) / R$.

Clearly, if the circuit is such that ωL is greater than $\frac{1}{\omega C}$, the current lags; if ωL is less than $\frac{1}{\omega C}$ the current leads, and if $\omega L = \frac{1}{\omega C}$ the capacity and inductance neutralise each other's effect, and *there is neither lag nor lead*: in this case the circuit is, in effect, *non-reactive*, although both capacity and inductance are present. When this condition obtains we have the phenomenon known as **electrical resonance,** a condition of importance in the study of wireless telegraphy and telephony.

We can now extend the preceding considerations to the case of the oscillatory circuits encountered in wireless telegraphy and telephony.

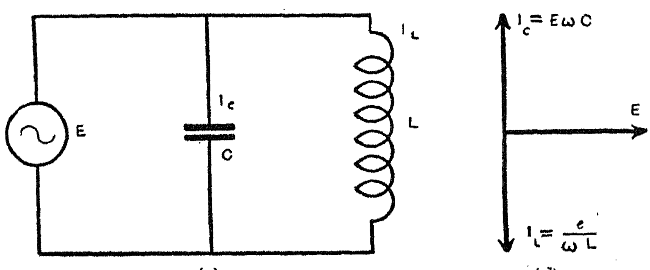


Fig. 1.

2. Inductance and Capacity in Parallel: Parallel Resonance.—The equations for an alternating current flowing through the circuit shown in Fig. 1 (*c*) are:—

$$\left.\begin{aligned} I_L &= \frac{E}{\sqrt{R^2 + \omega^2 L^2}} \\ \text{and} \qquad I_C &= E\omega C \end{aligned}\right\} \text{(R.M.S. values).}$$

where R = the resistance possessed by the inductance L,

C = the capacity of the condenser, $\omega = 2\pi \times$ the frequency $= 2\pi f$, and E = the applied P.D. If R is negligible compared with L:—

$$I_L = \frac{E}{\omega L}.$$

The currents are shown vectorially in Fig. 1 (*d*). Since in one the *lag* is 90° and in the other the lead is 90°, the two are 180° out of phase. The resultant current is, in this case, the *arithmetic difference* between the two.

If the values of L and C are such that the two currents are equal and opposite, *i.e.* if $I_L = I_C$, then:—

$$\frac{E}{\omega L} = E\omega C \quad \text{or} \quad \omega^2 = \frac{1}{LC},$$

$$\therefore \omega = \frac{1}{\sqrt{LC}},$$

and, since $\omega = 2\pi f$,

$$f = \frac{1}{2\pi\sqrt{LC}} \text{ cycles per second,}$$

where L is in henries and C is in farads.

This value of the frequency is called the **resonant frequency** of the circuit.

The condition obtained when $\omega^2 = \frac{1}{LC}$, and, therefore, $f = \frac{I}{2\pi\sqrt{LC}}$, in the above case is termed **parallel resonance.** In this condition the resultant current $(I_L - I_C)$ in the alternator is zero, although the current flowing through the inductance and condenser may be very large if C is large compared with L, since $I_L = \frac{E}{\omega L} = E\sqrt{\frac{C}{L}} = I_C$.

The values given above are all R.M.S. values, and the actual conditions are that the current flowing in the circuit formed by the inductance and condenser is an alternating current of frequency f, where $f = \frac{1}{2\pi\sqrt{LC}}$. Once this current has started to flow it will continue indefinitely (*provided the resistance is negligible*), but, of course, is a purely wattless current. (Watts = EI cos θ = zero if $\theta = 90°$.)

As no current is passing through the alternator the latter can be removed, and the current will still continue to flow through the inductance and condenser. Actually in practice, although the resistance may be negligible compared with the inductance, it is sufficient to prevent the current flowing indefinitely, and it causes the amplitude of the alternating current to decrease gradually. The energy dissipated in the resistance was, of course, stored in the condenser and inductance at the instant the alternator was removed, and the wastage was being supplied by the alternator by means of the power component of a very small current. This is shown vectorially in Fig. 2.

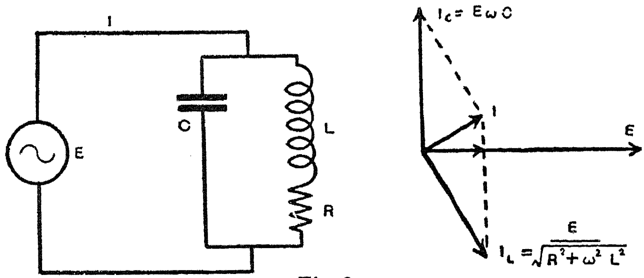


Fig. 2.

Instead of following a sine wave the instantaneous value of the current flowing after the alternator is removed gradually decreases in amplitude according to the equation:—

$$i = \mathrm{I}e^{-\frac{\mathrm{R}}{2\mathrm{L}}t}\sin(\omega t + \phi) \quad \text{(see p. 248)},$$

where $i =$ current at time t, $\tan\phi = \frac{\mathrm{R}}{2\mathrm{L}\omega}$, and $\omega = \sqrt{\frac{1}{\mathrm{LC}} - \frac{\mathrm{R}^2}{4\mathrm{L}^2}}$. The frequency is, therefore, given by:—

$$\text{Frequency} = f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{\mathrm{LC}} - \frac{\mathrm{R}^2}{4\mathrm{L}^2}},$$

and is called the **natural frequency** of the circuit. (If $\mathrm{R} = 0$ this becomes $f = 1/2\pi\sqrt{\mathrm{LC}}$ as before.) Fig. 3 shows how the current gets less and less in successive cycles.

If $R^2/4L^2$ is *greater than* $1/LC$, *i.e.* if $R > 2\sqrt{L}/\sqrt{C}$, no oscillations will continue, the current will be damped out quickly, and it will not change its direction. R *less than* $2\sqrt{L}/\sqrt{C}$ is the condition for oscillations. (See later).

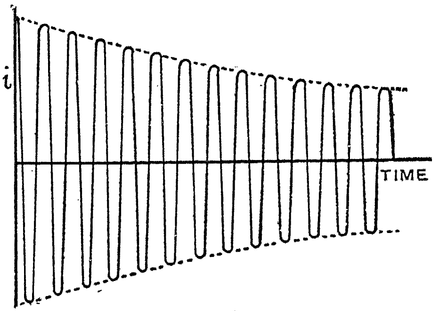


Fig. 3.

3. Oscillatory Currents.—If the values of resistance, inductance, and capacity in an alternating current circuit are such that when an alternating current, whose frequency is equal to the natural frequency of the circuit, is set up in the circuit, it continues to flow as an alternating current even after the supply is removed, the circuit is called an oscillatory circuit, and the current is called an oscillatory current. In other words, an oscillatory current is an alternating current flowing in a circuit whose resistance is very small, and where $f = \frac{1}{2\pi\sqrt{LC}}$ approximately, or more accurately

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}.$$

It is shown on subsequent pages that where these conditions prevail an oscillatory current can be set up in the circuit even without an alternating source of supply.

In ordinary alternating current circuits employed for lighting and power purposes, the frequency of the current is comparatively low, and rarely exceeds values of the order of fifty cycles per second. The equations given in the previous pages, however, are not based on any definite values of

frequency, and are true even if the frequency is of the order of millions of cycles per second, provided the values of resistance, inductance, and capacity are suitable. Usually in lighting and power circuits the resistance is so large and the frequency so low that, even if resonance occurs, the oscillatory current is damped out even before one complete oscillation takes place. In circuits used in wireless telegraphy and telephony, however, the resistance is purposely kept small, and the frequency employed may be of the order of millions.

Under these conditions the values of capacity and inductance used are much smaller than those employed for low frequencies, since $f = \frac{1}{2\pi \sqrt{LC}}$.

4. Damped Oscillations.—High frequency oscillations of the nature shown in Fig. 3, which are gradually decreasing in amplitude due to resistance or "damping" in the circuit, are called **damped oscillations.** The ratio of the amplitude of successive oscillations in the same direction is constant for a given circuit, and is equal to $e^{\frac{R}{2fL}}$, where e is the base of Napierian logarithms. (See p. 20.) The logarithm of this ratio is, therefore, constant for a given circuit, and is equal to $\frac{R}{2fL}$. It is usually denoted by δ, and is called the **logarithmic decrement** of the oscillation or wave.

It should be noted that the value of R in the above case is the total effective resistance of the circuit to high frequency oscillations, and is assumed to be small compared with the inductance. The well-known tendency of alternating current to confine itself to the surface of a conductor (known as **skin effect**) is much more pronounced in the case of oscillations of high frequency. The high frequency resistance of a circuit is, therefore, much greater than the resistance of the circuit to direct current or low frequency alternating current.

5. Undamped or Continuous Oscillations.—In the case of damped oscillations it has been shown that the damping

is due to the effective resistance of the circuit causing energy to be dissipated, without a corresponding supply of energy to replace it. If, however, sufficient energy can be supplied constantly to the circuit to replace that dissipated, the oscillations can be maintained of constant amplitude. Such an oscillation is called an **undamped** or **continuous oscillation,** and is shown in Fig. 4. It is, of course, a sine wave of high frequency provided no harmonics are present.

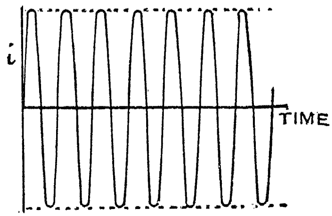


Fig. 4.

Returning to the original case of an alternator supplying a circuit containing an inductance, a condenser, and a resistance, it will be seen that this represents a circuit producing undamped oscillations. The oscillatory current flowing through the inductance and condenser is of large amplitude as the circuit is in resonance, and the only power supplied by the alternator is that required to make up the power dissipated in the circuit.

6. Series Resonance.—The equation for the current flowing in an alternating current circuit of the nature shown in Fig. 5 is :—

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}.$$

The voltage across the condenser equals $\frac{I}{\omega C}$, and the voltage across the inductance equals ωLI, and is 180° out of phase with the former. If these two voltages are equal :—

$$\frac{I}{\omega C} = \omega LI, \ i.e.\ \omega = \frac{1}{\sqrt{LC}}, \quad \therefore f = \frac{1}{2\pi\sqrt{LC}}.$$

This is the condition known as **series resonance.** If R is very small it will be seen that the voltage E applied to the circuit need only be small to cause a very large current to flow, as under these conditions $I = E/R$. The voltage across

the condenser, and also that across the inductance, may be extremely large, however, since they are each equal to ωLI.

Undamped oscillations will be produced as in the case of parallel resonance, described on p. 7, the alternator supplying the power required to replace the losses in the circuit. In this case, however, the power is supplied at a very low voltage but the current is large, and in the former case the voltage may be large and the current small.

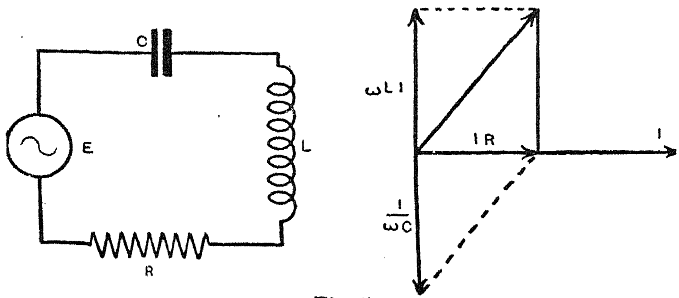


Fig. 5.

Suppose now that the circuit shown in Fig. 5 is modified by the introduction of a change-over switch as shown in Fig. 6. If the alternator be disconnected and the switch be moved over to the right, the oscillations will still continue to pass round the circuit including the condenser, inductance, resistance, and the short-circuited terminals of the switch, the conditions now being the same as those in the case of the arrangement shown in Fig. 2 when the alternator is removed. The oscillations will continue until the energy that was stored in the condenser and inductance is dissipated in the resistance. In this case, as in the former case, damped oscillations are produced.

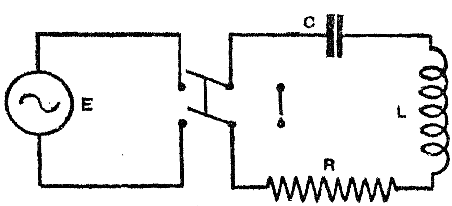


Fig. 6.

If the switch is changed over rapidly from left to right, merely allowing sufficient time for the oscillations to be damped out when the switch is to the right, a series of oscillations of the nature shown in Fig. 7 will be produced.

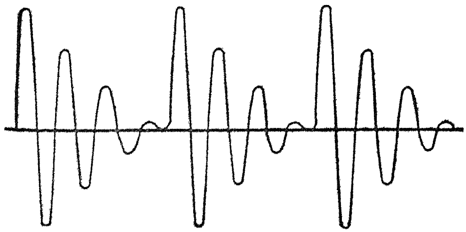


Fig. 7.

If the switch is moved to the right at the instant the voltage across the condenser is a maximum, the energy available in the circuit is that stored in the condenser $= \frac{1}{2}CV^2$, where V is the voltage across the condenser. The energy stored in the inductance is nil since the energy stored in an inductance $= \frac{1}{2}LI^2$, where I is the current flowing at that instant, and in this case $I = 0$. If the switch is changed over at any instant when the current is between maximum value and zero, part of the energy is stored in the inductance.

7. Production of Oscillatory Currents by the Discharge of a Condenser.—So far the arrangements considered for the production of oscillatory currents have involved the supply of power from an alternator of a frequency equal to that of the natural frequency of the circuit in which the oscillations have been produced. In practice such alternators are difficult to design, and, although they are used to some

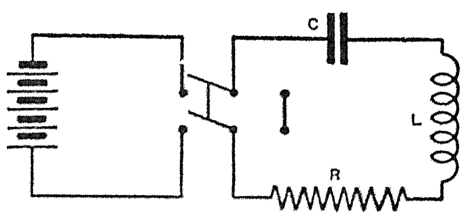


Fig. 8.

extent in wireless telegraphy, other methods of producing high frequency oscillations are much more common.

Suppose now that the alternator in Fig. 6 is replaced by a constant voltage direct current supply, as shown in Fig. 8. When the switch is placed to the left the condenser is charged up and no more current flows. The conditions are then identical with those in the arrangement shown in Fig. 6, at the instant when the voltage across the condenser is a maximum. If the switch be moved to the right, damped oscillations are produced as in the previous case, provided that the values of the capacity, inductance, and resistance are exactly as before. It will be seen, therefore, that if the switch is moved rapidly from left to right, a series of damped oscillations is produced as before, the time interval between each group of oscillations depending on the rate at which the switch is moved.

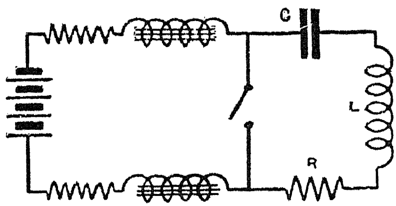


Fig. 9.

A single-way switch can be used instead of the change-over switch, provided inductive resistances are inserted in the connections to the battery to prevent the latter being short circuited, and to prevent oscillations passing back through the battery (Fig. 9). Since one group of oscillations passes each time the switch is closed, the rate of production of the groups of oscillations is exactly the same as the rate of closing the switch; in other words, the frequency of the groups of oscillations, as distinct from the frequency of the oscillations themselves, is equal to the frequency of the switch. The effect of alternately opening and closing the switch is simply to charge and discharge the condenser at the particular rate at which the switch is operated.

8. Production of Damped Oscillatory Currents by Means of a Spark-gap.—Now suppose the switch in Fig. 9 is replaced by a spark-gap of such a length that it breaks

down at the voltage of supply (Fig. 10). Until the condenser is charged up the voltage across the spark-gap is not sufficient to break down the gap; when the condenser is charged up, however, the gap breaks down, a conducting spark passes, and oscillations are set up as in the case of the circuit provided with the switch. The spark short-circuits the supply through the inductive resistances, and causes a drop in voltage across the spark-gap; consequently the spark

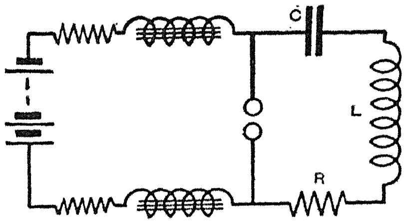


Fig. 10.

dies down, the condenser is charged up again, and the cycle of operations is repeated. The frequency of the groups of oscillations, *i.e.* the frequency of the spark, depends on the constants of the circuit.

If an alternating current supply be used instead of a direct current supply, the condenser is charged up each half-cycle, and the spark frequency will be twice that of the alternating supply. This method, and modifications of it, were the most common methods of producing high frequency oscillations for wireless telegraphy until a few years ago; they are now being superseded, however, by other methods which produce continuous or undamped oscillations

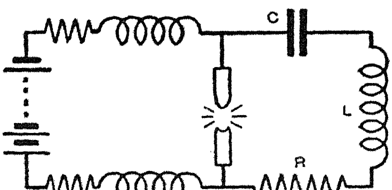


Fig. 11.

instead of damped oscillations.

9. Production of Undamped Oscillatory Currents by Means of an Arc.—Consider now the case of a similar circuit to the one shown in Fig. 10 with the spark-gap replaced by carbon electrodes, as shown in Fig. 11. Assuming the condenser to be charged up and an arc formed between the carbon electrodes, the conditions are the same

as those in the case of the spark-gap when a spark passes; an oscillatory current will, therefore, be started in the oscillatory circuit. During one half-cycle the oscillatory current will be flowing through the arc in the same direction as the main current through the arc from the battery, while during the next half-cycle the oscillatory current will be in the opposite direction to the main arc current.

If a carbon arc behaved exactly the same as a spark passing between two balls of metal the oscillations would be damped, and would gradually disappear, unless energy were supplied to the oscillatory circuit to replace that dissipated in the resistance. It is a peculiarity of a carbon arc, however, that its resistance and the difference of potential across it decrease as the current passing through it increases, and that the resistance and difference of potential increase as the current decreases. It follows, therefore, that when the direction of the oscillatory current is such that it increases the total current through the arc, the total resistance in the oscillatory circuit is decreased, and, therefore, the damping effect is reduced, and the oscillations tend to continue. When the oscillatory current is flowing in the opposite direction to the steady current through the arc the voltage across it increases, and, therefore, charges up the condenser until the P.D. across the arc reaches normal again, at which stage the condenser discharges, and the oscillatory current is maintained at constant amplitude.

It is evident, therefore, that the oscillatory currents produced by an arc are undamped or continuous oscillations, the energy dissipated in the oscillatory circuit being supplied by the direct current supply to the arc. A more detailed treatment of the arc as a means of producing undamped oscillations is given in Chapter IV.

10. Theory of the Discharge of a Condenser.—The conditions necessary for the production and maintenance of an oscillatory current are apparent when the discharge of a condenser is treated mathematically. The reader equipped with the necessary mathematical knowledge should turn to Art. 181 before proceeding further, and carefully study the full mathematical treatment of the discharge of a condenser there given. Even the reader who is not mathematically

inclined is advised to endeavour to understand the general line of argument by which the final conclusions are reached, even if he is not familiar with the actual methods of solution of a differential equation. A close study of that section will, in fact, be well worth the time and trouble involved.

At this stage, however, mainly for the benefit of the non-mathematical, we merely summarise the chief results obtained.

Fig. 12 represents a circuit containing a condenser, an inductance, and a resistance, the condenser being charged by the supply and then allowed to discharge through the inductance and resistance.

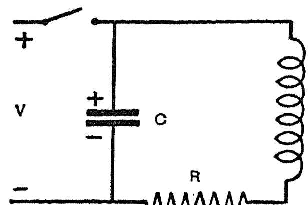


Fig. 12.

Let V = voltage across the condenser when charged,
Q = charge on the condenser at voltage V,
i = instantaneous value of the current at a time t after the condenser begins to discharge,
v = potential difference on the condenser at this time t.

In the investigation three cases arise:—

CASE I.—WHEN CR^2 IS GREATER THAN 4L, *i.e.* WHEN R IS GREATER THAN $2\sqrt{\frac{L}{C}}$.

It is proved on page 246 that:—

$$v = V\left(\frac{m_2}{m_2 - m_1} \cdot e^{m_1 t} - \frac{m_1}{m_2 - m_1} e^{m_2 t}\right) \quad \ldots\ldots (1)$$

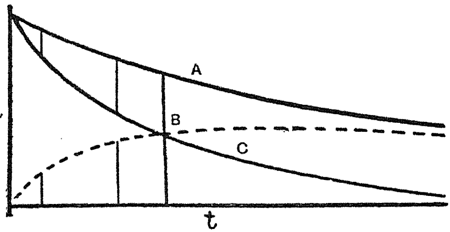
$$i = \frac{V}{\sqrt{R^2 - \frac{4L}{C}}}\left(e^{m_1 t} - e^{m_2 t}\right) \ldots\ldots\ldots\ldots\ldots (2)$$

where $$m_1 = -\frac{R}{2L} + \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

and $$m_2 = -\frac{R}{2L} - \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}.$$

Clearly (2) is *real* if m_1 and m_2 are real, *i.e.* if CR^2 is greater than 4L.

When $t = 0$, $i = 0$; and when $t = \infty$, $i = 0$; therefore there is a maximum value of i between these values of t: i is the difference between two expotential curves, and is shown in Fig. 198. The value of the current, therefore, rises to a maximum and then dies away to zero, *and is unidirectional.*



(A) $i = \dfrac{V}{\sqrt{R^2 - \dfrac{4L}{C}}} e^{m_1 t}$. (C) $i = \dfrac{V}{\sqrt{R^2 - \dfrac{4L}{C}}} e^{m_2 t}$.

(B) $i = \dfrac{V}{\sqrt{R^2 - \dfrac{4L}{C}}} \left(e^{m_1 t} - e^{m_2 t}\right)$.

Fig. 13.

The maximum value of the current is given by the expression:—

$$i_{\text{max}} = \frac{Q}{\sqrt{LC}} \cdot e^{-\frac{R}{2L}t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where t in this case has the value:—

$$t = \frac{\log_e m_1 - \log_e m_2}{m_2 - m_1}$$

It should be particularly noted that for the above values of the current to be real and, therefore, *for the discharge of the condenser to be unidirectional* CR^2 must be greater than $4L$. (See Art. 181.)

CASE II.—WHEN CR^2 IS LESS THAN $4L$, *i.e.* WHEN R IS LESS THAN $2\sqrt{\dfrac{L}{C}}$.

It is proved on page 248 that:—

$$e = Ve^{-at} \sqrt{1 + \frac{a^2}{\omega^2}} \left\{\cos(\omega t - \phi)\right\} \quad \ldots\ldots\ldots \quad (4)$$

$$i = \frac{V}{\omega L} e^{-at} \sin \omega t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where $\quad a = \dfrac{R}{2L}, \quad \omega = \sqrt{\dfrac{1}{LC} - \dfrac{R^2}{4L^2}}, \quad \tan\phi = \dfrac{a}{\omega}.$

The last equation represents an oscillatory current whose frequency is $\frac{\omega}{2\pi}$, and whose amplitude is equal to $\frac{V}{\omega L}\cdot e^{-at}$ and therefore decreases as the time increases; *i.e.* the oscillations are damped.

The frequency $\frac{\omega}{2\pi}$ of the oscillations is called the **natural frequency** of the circuit, and is equal to $\frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}$.

The term $\frac{R^2}{4L^2} = a^2$ determines the damping, and is therefore kept small if the losses are to be kept small, and can usually be neglected compared with $\frac{1}{LC}$. The frequency of the oscillations is, therefore, equal to $\frac{1}{2\pi\sqrt{LC}}$ for all practical purposes, and this value is called the **resonant frequency** of the circuit. The resonant frequency is, therefore, equal to the natural frequency when the damping is negligible.

It will be seen from page 11 that this agrees with the formula given there for the conditions for series resonance.

It should be particularly noted that *for an oscillatory discharge* CR^2 must be less than $4L$. (See Art. 2.)

CASE III.—WHEN $CR^2 = 4L$, *i.e.* WHEN $R = 2\sqrt{\frac{L}{C}}$.

The case when $CR^2 = 4L$ is a special case, and is not of practical importance. The solution is :—

$$i = \frac{V}{L}\cdot te^{-\frac{R}{2L}\cdot t} \quad \text{(6)}$$

$$v = Ve^{-\frac{R}{2L}\cdot t}\left(1 - \frac{R}{2L}\cdot t\right) \quad \text{(7)}$$

As already indicated, the above is a brief summary only of the main results obtained from the mathematical investigation of the discharge of a condenser: the full treatment is given on pages 244-249.

11. Logarithmic Decrement.—As stated on page 10, the logarithm of the ratio of the amplitudes of successive

oscillations in the same direction is constant for a given circuit, and is called the logarithmic decrement of the oscillations.

We have seen that $i = \frac{V}{\omega L} \cdot e^{-at} \sin \omega t$, and by a simple application of the calculus it can be shown that for maximum current:—

$$\tan \omega t = \frac{\omega}{a}.$$

Thus for maximum current:—

$$\frac{di}{dt} = 0, \text{ i.e. } \frac{V}{\omega L}\left(e^{-at}\,\omega \cos \omega t - ae^{-at} \sin \omega t\right) = 0;$$

$$\therefore \tan \omega t = \frac{\omega}{a}.$$

If t_1 is the time for the first maximum value:—

$\omega t = \omega t_1 + n\pi$ for all other maximum values.

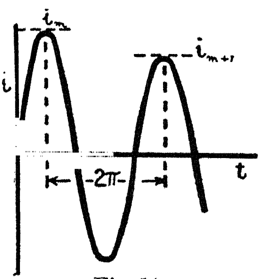


Fig. 14.

If i_m is a maximum value in one direction and i_{m+1} is the next maximum value in the same direction, $n = 2$. (See Fig. 14).

$$\therefore \frac{i_m}{i_{m+1}} = \frac{e^{-at}}{e^{-a\left(t + \frac{2\pi}{\omega}\right)}}$$

$= e^{\frac{2\pi a}{\omega}}$, which is constant.

The logarithm of this ratio is therefore, equal to $\frac{2\pi a}{\omega}$, which is the logarithmic decrement. Hence:—

$$\delta = \frac{2\pi a}{\omega} = a\mathrm{T}\left(\text{where } \mathrm{T} = \frac{1}{f} \text{ and } f = \frac{\omega}{2\pi}\right)$$

$$= \frac{\mathrm{R}}{2f\mathrm{L}}.$$

If it be assumed that a series of oscillations is finished when the amplitude reaches 1 per cent. of the initial value, and that the number of periods, or oscillations, before this occurs is equal to N, then $e^{a\mathrm{TN}} = 100$, since the ratio

between successive oscillations in the same direction is equal to $e^{\alpha T}$.

$$\therefore \alpha TN = N\delta = \log_e 100$$

$$\therefore N = \frac{4{\cdot}6}{\delta}.$$

This value of N neglects the first half of the first oscillation and the last half of the last oscillation, since the oscillation starts and finishes at zero; therefore, if the first and last oscillations are counted, the number of oscillations occurring before the amplitude reaches 1 per cent. of the initial amplitude $= \frac{4{\cdot}6}{\delta} + 1$.

The product of the frequency and the logarithmic decrement is sometimes employed and is known as the **damping factor** $\left(= \frac{R}{2L}\right)$.

12. R.M.S. Value of Damped Oscillations.—The value of the current at any time t after the commencement of the oscillation is given by the following formula (see page 248) for a series of damped oscillations:—

$$i = \frac{V}{\omega L} e^{-\alpha t} \sin \omega t.$$

The total energy dissipated per second is equal to $\frac{NV^2C}{2}$ where N is equal to the number of discharges of the condenser per second. The total energy dissipated per second is also equal to the losses in the effective resistance of the circuit, *i.e.* it is equal to $I^2_{\text{R.M.S.}} \times R$.

$$\therefore I_{\text{R.M.S.}} = \sqrt{\frac{NV^2C}{2R}}$$

$$= \frac{V}{2\omega L}\sqrt{\frac{NC2\omega^2L^2}{R}}$$

$$= \frac{V}{2\omega L}\sqrt{\frac{N \, . \, 2L}{R}} \, . \; \omega\sqrt{LC}.$$

$$\text{Now } \alpha = \frac{R}{2L} \quad \text{and} \quad \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} = \frac{1}{\sqrt{LC}} \text{ approx.}$$

$$\therefore I_{\text{R.M.S.}} = \frac{V}{2\omega L}\sqrt{\frac{N}{\alpha}} \text{ approx.}$$

$$= \frac{I \text{ max.}}{2}\sqrt{\frac{N}{\alpha}} \text{ approx.}$$

$$= \frac{I \text{ max.}}{2}\sqrt{\frac{N}{\delta f}} \text{ approx.}$$

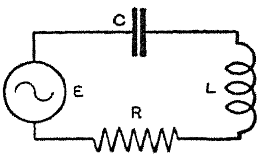


Fig. 15.

13. Forced Oscillations.—Consider a high frequency current flowing in the circuit shown in Fig. 15, the source of supply being, for example, a high frequency alternator.

The current flowing is represented by the formula :—

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \qquad \text{(R.M.S. values)}$$

as in ordinary low frequency alternating current circuits.

The resonant frequency of the circuit is given by :—

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}}.$$

When the frequency of the high frequency supply to the circuit is equal to the resonant frequency of the circuit resonance occurs, and the value of the current is equal to $\frac{E}{R}$. When the frequencies are different an oscillatory current flows in the circuit and its frequency is that of the supply. The oscillations in such a case are called **forced oscillations,** and of course they are of small magnitude compared with the oscillations produced by an equal E.M.F. at resonant frequency.

If R is small compared with $\omega_0 L$ and $\frac{1}{\omega_0 C}$ a small change in ωL or $\frac{1}{\omega C}$, *i.e.* a slight departure from resonance, will cause a large change in the value of the current. This is illustrated in Fig. 16, which shows two typical "resonance curves."

If, however, R is comparable with ωL and $\frac{1}{\omega C}$ the effect of a small change in the frequency near the resonant frequency is not so marked, and a flat-topped resonance curve is obtained of the nature shown in Fig. 16.

It will be seen, therefore, that the effect of applying a high frequency alternating E.M.F. to a circuit is much greater when the frequency is equal to the natural frequency of the circuit, than when the frequency is different. In the latter case forced oscillations of small amplitude are produced.

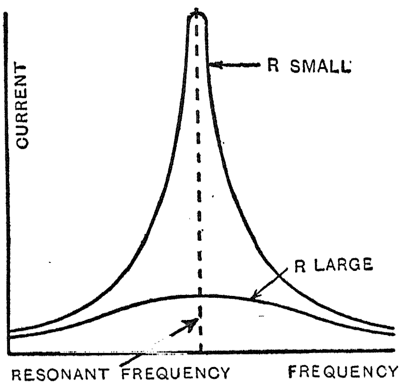


Fig. 16.

In the case considered above it has been assumed that the oscillations produced are continuous or undamped, the supply being from an alternator; if the E.M.F. supplied to the circuit had been a damped oscillatory E.M.F., produced by a circuit containing a spark gap, for example, the forced oscillations would not have been of such a simple nature. Forced oscillations produced in this manner are dealt with on page 25.

14. Coupled Oscillatory Circuits.—If two ordinary alternating current circuits are coupled together as shown in Fig. 17 an alternating current is induced in the secondary circuit and its frequency is equal to that of the current in

the primary. If both circuits are in resonance the current will be limited only by the resistance.

The E.M.F. induced in the inductance L_2 depends upon the rate of change of the flux passing through it, which depends on the number of turns in each of the two inductances, L_1 and L_2, and upon the mutual induction M between the two inductances, assuming the frequency of the current to be constant.

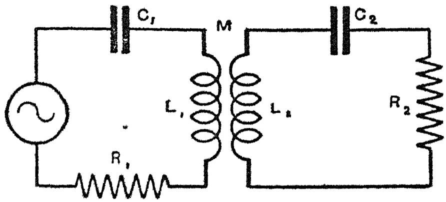


Fig. 17.

The mutual induction between two coils is equal to the number of lines of force linked through one coil due to unit current in the other, and is therefore proportional to the product of the number of turns in one coil and the number of turns in the other. Since the inductance of a coil is proportional to the square of the number of turns in the coil the mutual induction between two coils is proportional to the square root of the product of the inductances of the coils, *i.e.* $M \propto \sqrt{L_1 L_2}$.

If there is no leakage between the two inductances M is obviously equal to $\sqrt{L_1 L_2}$.

The ratio $M/\sqrt{L_1 L_2}$ is called the **coefficient of coupling,** and is usually denoted by k: that is:—

$$k = \text{coefficient of coupling} = \frac{M}{\sqrt{L_1 L_2}}, \quad \therefore M = k\sqrt{L_1 L_2},$$

where k is always less than unity. If the coefficient is small the coils are said to be **loose** coupled, if high the coupling is said to be **tight.**

In high frequency alternating current circuits very large losses would be introduced if iron cored inductances or transformers were used, since hysteresis losses in iron are proportional to the frequency and eddy current losses are

proportional to the square of the frequency. It is usual, therefore, to avoid introducing iron into high frequency circuits; consequently a large amount of leakage occurs between two coils coupled together in high frequency circuits and the coefficient of coupling is therefore usually very small.

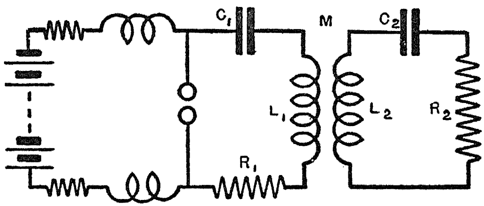


Fig. 18.

Now consider the case where a secondary circuit is coupled to a primary circuit in which damped oscillations, instead of undamped oscillations, are flowing as shown in Fig. 18.

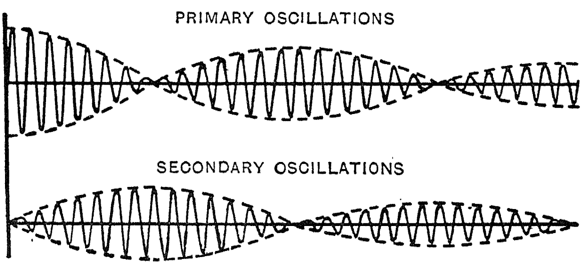


Fig. 19.

When a series of damped oscillations flows in the primary circuit damped oscillations will be set up in the secondary circuit if the latter is in resonance or tune. As, however, the oscillations in the primary start with the primary condenser fully charged they start at maximum amplitude, while the oscillations in the secondary have to charge up the secondary condenser before maximum amplitude is reached.

Consequently when the oscillations in the secondary have maximum amplitude the oscillations in the primary are dying

away. As the spark is still passing the primary circuit is still a closed circuit and the oscillations in the secondary begin to induce oscillations in the primary, which in turn induce another train of oscillations in the secondary and so on until all the energy is dissipated and a fresh supply is received by the passage of another spark.

If the coupling is weak the energy returned to the primary circuit is much less than with a tight coupling, and therefore more energy is dissipated in the secondary circuit and less in the primary circuit.

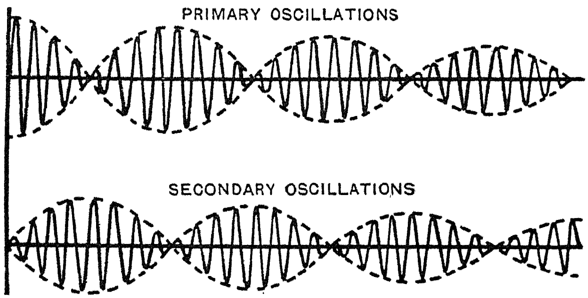


Fig. 20.

The nature of the oscillations in the primary and secondary circuits for tight coupling is indicated in Fig. 19, and for loose coupling in Fig. 20.

The transference of energy backwards and forwards from one oscillatory circuit to another is analogous to the coupled system of pendulums shown in Fig. 21. If pendulum A is set in motion while B is stationary the swing of A gradually dies away and B is set in motion and reaches its maximum swing when A comes to rest. B then gradually comes to rest and A gradually starts to swing again and reaches maximum amplitude when B comes to rest. The energy continues

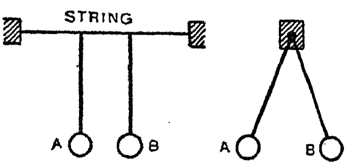


Fig. 21.

to be transferred backwards and forwards until it is all dissipated. The coupling can be varied by altering the length of string connecting the two pendulums. If the reader desires to study mechanical analogies further he is referred to the paper by Prof. C. F. Jenkin in *Journal I.E.E.*, 1922, Vol. 60, No. 312.

It will be seen from Figs. 19 and 20 that the effect of the interchange of energy between the two circuits is the same as that of an oscillating current represented by the dotted lines. The frequency of this oscillation is much less than the natural frequency of the circuit, and in fact is equal to the difference between two frequencies, one of which is slightly greater than the frequency of the circuit, and the other slightly less. This effect is similar to the production of beats in the case of sound.

The explanation of the production of two waves of different frequencies, whose resultant is indicated by the dotted curves, is that the effect of mutual induction between the two circuits affects the value of the inductance of each circuit.

When the current in the primary is flowing in one direction the effect of mutual induction is to increase the inductance of the secondary, and when the current in the primary is flowing in the opposite direction the effective inductance of the secondary is decreased.

The effective inductance in one case is $L_2\sqrt{1+k}$ and in the other case $L_2\sqrt{1-k}$; consequently the two frequencies f_1 and f_2 are:—

$$f_1 = f_0 \times \frac{1}{\sqrt{1-k}}$$

$$f_2 = f_0 \times \frac{1}{\sqrt{1+k}}$$

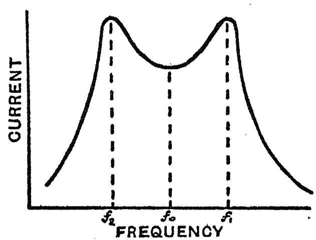
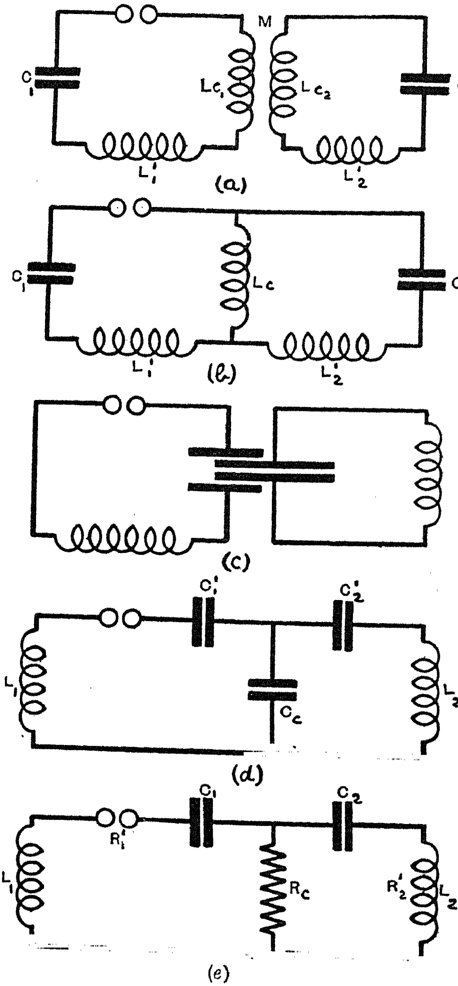


Fig. 22.

where f_0 is the resonant frequency of the primary and secondary circuits. Similarly the inductance of the primary becomes $L_1\sqrt{1+k}$ and $L_1\sqrt{1-k}$, and therefore oscillations of the same two frequencies are present in the primary.



(a)

$$k = \frac{M}{\sqrt{L_1 L_2}}$$
$$L_1 = L'_1 + L_{c1}$$
$$L_2 = L'_2 + L_{c2}$$

(b)

$$M = L_c$$
$$L_1 = L'_1 + L_c$$
$$L_2 = L'_2 + L_c$$
$$k = \frac{L_c}{\sqrt{(L'_1 + L_c)(L'_2 + L_c)}}$$

(c)

Not practicable.

(d)

$$C_1 = \frac{C'_1 C_c}{C'_1 + C_c} = \text{Primary capacity}$$
$$C_2 = \frac{C'_2 C_c}{C'_2 + C_c} = \text{Secondary capacity}$$
$$k = \sqrt{\frac{C_1 C_2}{C_c^2}}$$

(e)

$$R_1 = R'_1 + R_c$$
$$R_2 = R'_2 + R_c$$
$$k = \frac{R_c}{\sqrt{R_1 R_2}}$$

Fig. 23.

If a resonance curve be plotted for either the primary or the secondary it will be of the form shown in Fig. 22. By making k sufficiently small f_1 and f_2 can be made equal to f_0 and the two peaks in the resonance curve coincide. This means that if the oscillations are to have one frequency only the coupling must be **loose.** Tight coupling produces oscillations of two frequencies.

15. Methods of Coupling Circuits.—In addition to the method of coupling oscillatory circuits shown in Figs. 17 and 18 there are several other methods. The various methods that may be used are as follows :—

(*a*) Magnetic coupling due to mutual induction between two separate circuits (*e.g.* transformer coupling, as in Figs. 17 and 18).

(*b*) Magnetic coupling due to mutual induction between two circuits which have some coil or coils in common (*e.g.* an auto-transformer).

(*c*) Electric or capacity coupling due to the induction of E.M.F. by the electric field of the other circuit, the two circuits being separate.

(*d*) Electric or capacity coupling by a condenser common to both circuits.

(*e*) Resistance coupling by means of a resistance common to both circuits.

All the above methods, except (*c*), are largely used in practice; it is not convenient, however, to use method (*c*).

Examples of the various methods are shown in Fig. 23.

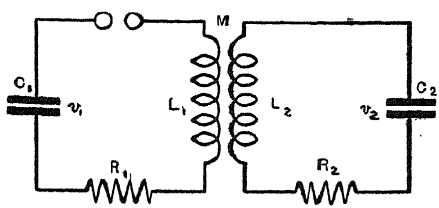


Fig. 24.

16. Theory of Coupled Oscillatory Circuits.—As in Art. 10, the full mathematical treatment of coupled oscillatory circuits is given in Chapter XIII. (p. 249), and readers who have the necessary mathematical knowledge should, at this stage, carefully study that treatment. In the present

section a brief summary of the main points only is given for the benefit of those unable to follow the mathematics in detail.

Let i_1 and i_2 be the instantaneous values of the currents in the primary and secondary circuits shown in Fig. 24.

It is proved on page 250 that :—

$$i_1 = A_1'e^{-a't}\cos(\omega_1 t - \phi_1') + A_1''e^{-a''t}\cos(\omega_2 t - \phi_1''),$$

$$i_2 = A'_2e^{-a't}\cos(\omega_1 t - \phi_2') + A_2''e^{-a''t}\cos(\omega_2 t - \phi_2''),$$

and, without going into the details of the various terms in these equations here, the solutions show that there are two oscillations of different frequencies present in the secondary circuit, and also in the primary, as described on page 27.

If the damping is small (which is usually the case in the oscillatory circuits employed in wireless telegraphy), and the two circuits are in tune, then if f_1 and f_2 are the frequencies of the two sets of oscillations,

$$f_1 = \frac{f_0}{\sqrt{1-k}} \text{ and } f_2 = \frac{f_0}{\sqrt{1+k}},$$

where f_0 is the natural frequency of each circuit.

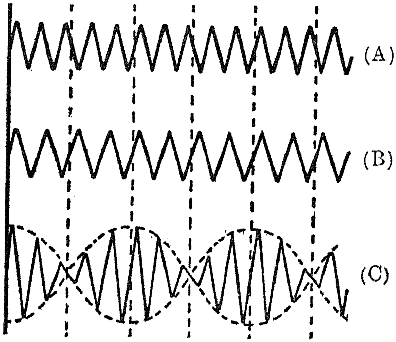
The above results are arrived at on the assumption that the damping is negligible. If the logarithmic decrement of the secondary is less than about 0.2 the error is not greater than about 5 per cent.

The resultant effect of the two sets of oscillations is to produce an oscillation whose frequency is equal to $f_1 - f_2$. This can be shown by adding the instantaneous values of the two currents, and it is proved on page 252 that the instantaneous value of the resultant current is given by:—

$$i = 2A\left[\cos\left\{2\pi\left(\frac{f_1 - f_2}{2}\right)t - \theta_1\right\} \times \cos\left\{2\pi\left(\frac{f_1 + f_2}{2}\right)t - \theta_2\right\}\right].$$

This represents an oscillation whose amplitude is represented by $2A \cos\left\{2\pi\left(\frac{f_1 - f_2}{2}\right)t - \theta_1\right\}$, and whose frequency is $\frac{(f_1 + f_2)}{2}$. The amplitude becomes a maximum every time $\cos\left\{2\pi\left(\frac{f_1 - f_2}{2}\right)t - \theta_1\right\} = 1$, which occurs $f_1 - f_2$ times a

second. Hence the frequency of the complex oscillation is $f_1 - f_2$, since its maximum value occurs $f_1 - f_2$ times a second, but the frequency of individual oscillations composing the complex oscillation is $\frac{f_1 + f_2}{2}$, which is the mean of the frequencies of the two separate oscillations.



(A) $i_1 = A \cos (2\pi f_1 t - \phi_1)$.
(B) $i_2 = A \cos (2\pi f_2 t - \phi_2)$.
(C) $i = i_1 + i_2$.

Fig. 25.

Fig. 25 represents the oscillations of frequencies f_1 and f_2 and their resultant.

As already indicated, the above is a brief summary only of some of the results obtained from the mathematical investigation of coupled circuits: the full treatment is given on pages 249-253.

CHAPTER II.

ELECTROMAGNETIC WAVES AND THEIR PROPAGATION.

17. Radiating Oscillatory Circuits.—In Chapter I. the oscillatory circuits considered have been treated as ordinary alternating current circuits with certain relations between the inductance, capacity, resistance and frequency.

The value of the resistance in all cases has been taken as the "effective value," *i.e.* as the value of the resistance necessary to account for all the losses in the circuit, assuming them all to be due to the resistance. Such losses as may occur in the dielectric of the condenser, eddy currents, and hysteresis have all been allowed for in the **effective resistance** which determines the damping.

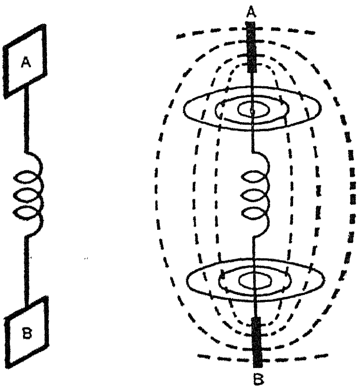


Fig. 26.

Now consider what happens if part of the magnetic field due to the current in an oscillatory circuit occupies the same space as part of the electric field due to the condenser. This condition can be obtained most readily by separating the plates of the condenser sufficiently as shown in Fig. 26. Under these conditions the magnetic field at certain parts of the space surrounding this open oscillatory circuit will be at right angles to the electrostatic field. Clerk Maxwell showed mathematically that such conditions represent a storage of energy moving in a direction at right angles to both these fields.

Maxwell's calculations assumed the presence of some medium through which electromagnetic action could take place between two conductors of electricity or two magnets. He assumed that when a condenser became charged up there was a displacement of the dielectric between the plates so that the dielectric was under strain. Discharging the condenser allowed the dielectric to regain its normal state. He thus looked upon the change of electric strain as equivalent to a current, and so completed the circuit through the dielectric.

The modern conception of the construction of all matter is that each atom consists of a positive nucleus of electricity surrounded by negative charges of electricity, called **electrons,** moving with high velocities. The difference between atoms of different substances is caused by the number and arrangement of these electrons. In a conductor of electricity the flow of electricity is due to the passage of these electrons from one atom to another, and in the case of a dielectric a momentary current is caused by the displacement only of these electrons. The displacement of electrons in a dielectric is produced by a change in the electric field, and is therefore equivalent to a current, and produces a magnetic field while the displacement is taking place.

In order to explain electromagnetic action across space containing no form of matter which could be taken to be the medium, it has been necessary to assume the existence of a suitable medium which has these properties. This medium is called the **ether.** Whether such a medium exists and of what it consists has not yet been settled, but the assumption of its existence has enabled theory to agree with practice up to the present.

On the assumption of such a medium Maxwell showed that light and electromagnetic waves were the same form of energy and were transmitted by wave motion, the difference between them being simply one of frequency or wave length, the velocity being the same in all cases where the medium was the same. Subsequent experiments have shown the correctness of Maxwell's theory, and electromagnetic waves have been reflected and polarised, etc., in exactly the same manner as light.

Assuming then, for the present, that the presence of an electric field and a magnetic field at right angles in the same

space produces a motion of energy in a direction at right angles to both of them, the necessity for oscillatory currents to produce such conditions regularly and so cause a regular flow of energy will be seen. It should be noted that the reversal of one of the fields causes a reversal of the direction of the flow of energy, but that the reversal of the directions of both fields causes no change in the direction of flow of the energy.

It will be seen that the electric and magnetic fields produced by an oscillatory circuit of the nature shown in Fig. 26 would be exactly 90° out of phase, and no energy could be radiated if there were no effective resistance in the circuit. Actually, however, they are not quite 90° out of phase owing to effective resistance in the circuit, so there is evidently a small component of one field in phase with the other and energy can be radiated. This radiated energy is equivalent to the dissipation of energy in a fictitious resistance included in the effective resistance of the circuit, and is called the **radiation resistance** of the oscillatory circuit.

The components of the electric and magnetic fields producing radiation are therefore oscillatory and must be in phase to produce radiation of energy which is of varying amounts but unidirectional. The other components of the two fields cause energy to oscillate backwards and forwards in the space occupied by the two fields.

An oscillatory circuit capable of radiating energy in the form of waves is called an **open** or **radiating** oscillatory circuit. The amount of energy radiated will depend on the strengths of the electric and magnetic fields at right angles. High voltages and large currents are therefore necessary for the radiation of large amounts of energy.

18. Transmission of Energy by Direct Current.—An idea of the part played by the electric and magnetic fields in the transmission of energy can be obtained by the consideration of the transmission of energy by direct currents.

Consider a direct current transmission line composed of two wide parallel strips of thin copper placed close together as shown in Fig. 27 (*a*). The electric and magnetic fields will be approximately uniform in the space between the

there is a transmission of energy per unit area in a direction at right angles to the plane of H and E given by the expression:—

Rate of transmission per unit area $= \frac{10\ HE}{4\pi}$ watts, where E is in volts per centimetre.

On short-circuiting the line at the far end there is a magnetic field, but no electric field as the P.D. falls to zero, and on opening the line the magnetic field becomes zero, but there is an electric field. No energy is transmitted, however, in either case.

It will be seen, therefore, that energy is transmitted through space when electric and magnetic fields exist simultaneously and have components at right angles.

The treatment given above, and also that in the next section, are due to Professor Howe.[1]

19. Transmission of Energy by Alternating Current.—From the previous section it will be seen that the inductance of the transmission line per centimetre of length, *i.e.* the flux produced in the space between the conductors by unit current, is $\frac{4\pi d}{b}$ absolute units or $\frac{4\pi}{10^9} \cdot \frac{d}{b}$ henries.

The capacity between the conductors per cm. of length is $\frac{b}{4\pi d}$ absolute units or $\frac{b}{4\pi d \times 9 \times 10^{11}}$ farads if the dielectric is air.

Now consider the same transmission line with an alternating source of supply instead of a direct supply. The inductance and capacity of the line can be represented by an inductance L and a capacity C every centimetre, where $L = \frac{4\pi d}{b}$ absolute units and $C = \frac{b}{4\pi d}$ absolute units as given above.

Fig. 28 represents the transmission line, the resistance of the conductors and the leakage being assumed to be negligible. The load is assumed to be non-inductive.

The current in the conductor at any point can be found by constructing a vector diagram. Let I_o = R.M.S. value of

[1] See *Electrician*, Vol. LXXI., p. 965, Sept. 19th, 1913.

current at receiving end, V_o = R.M.S. value of voltage at receiving end, f = frequency of alternator, $\omega = 2\pi f$, R = resistance of load.

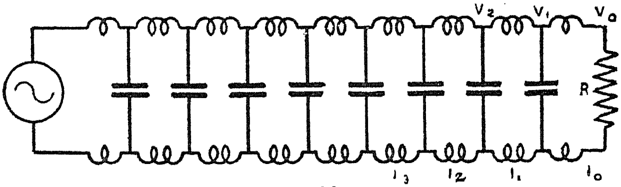


Fig. 28.

If I be the R.M.S. value of the current at any point on the line the voltage drop per centimetre at that point will have an R.M.S. value of ωLI and will be 90° out of phase with the current. Similarly if V be the R.M.S. value of the P.D. between the lines at any point the capacity current per centimetre at that point will have an R.M.S. value of ωCV and will be 90° out of phase with V.

If I and V are assumed to be in phase and of constant value at all points the vectors representing them must rotate with the same angular velocity and will each describe a circle as shown in Fig. 29. The difference in voltage or current between any two points is measured along the arc of the corresponding circle from the ends of the vectors representing the conditions at those points. If the points are one centimetre apart the difference in current will be ωCV and the difference in voltage will be ωLI. Consequently $\frac{\omega CV}{I} = \frac{\omega LI}{V}$ since the angular velocities are the same.

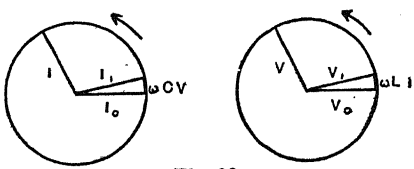


Fig. 29.

$$\text{Hence } \frac{V}{I} = \sqrt{\frac{L}{C}}.$$

$$\text{Now } \frac{V}{I} = \frac{V_o}{I_o} = R, \text{ therefore } R = \sqrt{\frac{L}{C}}.$$

Thus if the resistance of the non-inductive load is equal to $\sqrt{\frac{L}{C}}$ the R.M.S. values of the current and voltage are constant all along the line and the current and voltage are in phase at any point.

If the distance between any two points on the line is l cm. the difference in voltage will be ωLIl and this is measured along the arc of the circle described by vector V. If $\omega LIl = 2\pi V$ the voltages at both points will be in phase,

hence
$$l = \frac{2\pi V}{\omega LI} = \frac{2\pi}{\omega\sqrt{LC}} = \frac{1}{f\sqrt{LC}} \text{ cm.}$$

Thus it is seen that the voltage and current at any point on the transmission line are in phase with each other and with the voltage and current at all points distant $\frac{1}{f\sqrt{LC}}$ cm. or a multiple thereof. The distance $\frac{1}{f\sqrt{LC}}$ cm. therefore represents the wave length and is denoted by λ. The velocity of the wave is equal to $\lambda f = \frac{1}{\sqrt{LC}}$.

It will be seen that the velocity is independent of the frequency and is therefore constant for a given transmission line. Substituting the values of L and C as given on page 36 the velocity is equal to

$$\frac{1}{\sqrt{b/4\pi d \times 4\pi d/b \times 1/(9 \times 10^{20})}} = 3 \times 10^{10} \text{ cm. per second.}$$

This velocity is the same as the velocity of light, and this fact is one of the chief reasons for believing that light and electromagnetic waves are the same form of energy but of different wave lengths. Since $\frac{V}{I}$ is constant all along the line and equal to $\sqrt{\frac{L}{C}}$ it is evident that $\frac{LI^2}{2} = \frac{CV^2}{2}$, which means that the total energy in each cubic centimetre of the dielectric is equally divided between the magnetic and electric fields at every moment.

The total energy in 1 cm. of the line is evidently CV^2 and this is being transferred with a velocity equal to $\frac{1}{\sqrt{LC}}$, hence the energy arriving at the receiving end is

$$CV^2 \times \frac{1}{\sqrt{LC}} = V^2 \times \sqrt{\frac{C}{L}} = \frac{V^2}{R} \text{ joules.}$$

If the resistance be replaced by a choking coil or condenser with negligible losses the voltage and current vectors will be 90° out of phase all along the line. There will be no transmission of energy but energy will be stored alternately in the magnetic and electric fields. In this case stationary waves are produced.

If the resistance is not equal to $\sqrt{\frac{L}{C}}$ all the energy arriving at the receiving end is not absorbed by the resistance, but some of it is reflected back and produces waves of energy travelling in the opposite direction to the main waves.

Another method of treating the transmission of electromagnetic waves is given in the next section.

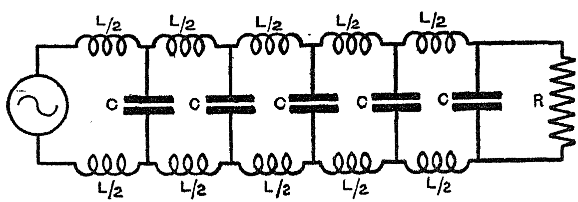


Fig. 30.

20. Transmission of Electromagnetic Waves along Wires.—The nature of electromagnetic waves and their propagation can be best understood by considering the case of waves along wires. This has been dealt with in Art. 19, and a mathematical treatment is given in Chapter XIII. The reader with the necessary knowledge should study that treatment before proceeding further: in this section the facts are merely summarised.

Consider the transmission line of Fig. 30. Let C = capacity, and L = inductance, per unit length. On page 254 it is proved that if i and v = current and potential at distance x from receiving end:—

$$i = \text{A} \cos \omega\sqrt{\text{LC}} \,.\, x + \text{B} \sin \omega\sqrt{\text{LC}} \,.\, x.$$

$$v = \text{A}' \cos \omega\sqrt{\text{LC}} \,.\, x + \text{B}' \sin \omega\sqrt{\text{LC}} \,.\, x.$$

Let i_2 = current at receiving end, *i.e.* when $x = 0$, then $i_2 = \text{A}$.

Similarly, if x be taken from sending end and i_1 = current at sending end, then $i_1 = \text{B}$.

$$\therefore\ i = i_1 \sin \omega\sqrt{\text{LC}} \,.\, x + i_2 \cos \omega\sqrt{\text{LC}} \,.\, x,$$

$$\text{and } v = v_1 \sin \omega\sqrt{\text{LC}} \,.\, x + v_2 \cos \omega\sqrt{\text{LC}} \,.\, x.$$

These equations show that the current at any point is the sum of two currents, the value of one of these currents varying according to a sine law as x varies, and the other varying according to a cosine law. Thus the effect is that of a wave moving along the transmission line from the sending end, being reflected at the receiving end, and travelling back from there.

Similarly, there are two waves of voltage, each being in phase with its corresponding current wave.

At all points along the line for which $\omega\sqrt{\text{LC}}.x$ is equal to a multiple of 2π, the value of the current due to a wave is constant, therefore the distance between all these points is $\frac{2\pi}{\omega\sqrt{\text{LC}}}$. The distance between two points where the value of the current is always identical is called the **wave-length** of the wave, therefore the wave-length in this particular case is equal to $\frac{2\pi}{\omega\sqrt{\text{LC}}} = \lambda$.

The wave advances this distance in one cycle, therefore the velocity of the wave along the line is equal to the frequency multiplied by the wave-length, *i.e.* equal to $\frac{2\pi}{\omega\sqrt{\text{LC}}} \cdot f = \frac{\omega}{\omega\sqrt{\text{LC}}} = \frac{1}{\sqrt{\text{LC}}}$; thus the velocity is constant whatever the frequency.

If the dielectric is air, the capacity of two parallel wires, radius r, at a distance d apart is given by the formula :—

$$C = \frac{1}{4 \log_e \frac{d}{r}} \times \frac{1}{9 \times 10^{11}} \text{ farads,}$$

and the inductance is given by :—

$$L = 4 \log_e \frac{d}{r} \times \frac{1}{10^9} \text{ henries.}$$

Hence $\qquad \text{velocity} = \dfrac{1}{\sqrt{LC}} = 3 \times 10^{10}$ cm./sec.

Thus it is seen that all electromagnetic waves travelling along wires with air as the dielectric travel with a velocity of 3×10^{10} centimetres per second, which is equal to the velocity of light.

Under certain conditions the reflected wave can be made equal to zero. If R, the resistance at the receiving end, $= \sqrt{\frac{L}{C}}$, it can be shown that all the energy received is absorbed in R, and none is reflected. If there is no reflection, then :—

$$i = i_1 \sin \omega \sqrt{LC} \,.\, x, \text{ and } v = v_1 \sin \omega \sqrt{LC} \,.\, x.$$

$$\therefore \frac{v}{i} = \frac{v_1}{i_1}.$$

Hence the ratio of voltage to current at any instant is the same all along the line, and is equal to R, since $v_2/i_2 = R$.

As already indicated, the above is a brief summary only of some of the results obtained from the mathematical investigation of the transmission of waves along wires : the full treatment is given in Chapter XIII.

21. Electromagnetic Waves in the Ether.—In preceding sections it has been shown how electromagnetic waves can be transmitted along wires or strips. These waves are of the simple type known as plane waves, *i.e.* they are radiated in one direction only from the supply, and do not flow in all directions.

If the upper strip is made several hundred miles wide and placed several hundred feet from the earth, which replaces

the lower strip, no essential change is made in the transmission line, and plane electromagnetic waves will then sweep over the surface of the earth.

Now consider an arrangement with the upper strip replaced by an inverted cone, as shown in Fig. 31, the alternator being connected between the apex of the cone and the earth.

The electromagnetic waves now sweep out in all directions. The magnetic flux will be situated entirely between the discs, and will be in opposite directions in alternate concentric belts round the alternator. The current flows alternately outwards and inwards radially with respect to the alternator.

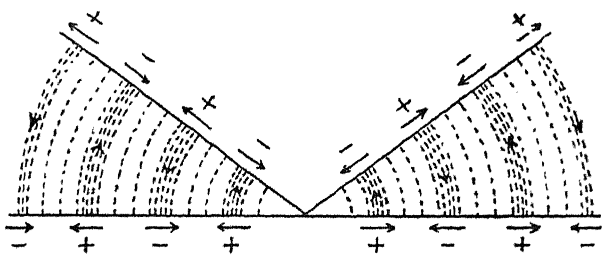


Fig. 31.

The inductance and capacity per radial centimetre are constant, as in the ordinary transmission line, and do not vary with the distance from the origin, so the same calculations apply as for the ordinary transmission line, except that the strengths of the electric and magnetic fields vary inversely as the distance from the apex of the cone.

These statements can be proved in the following manner:—

Let $a =$ angle between cone and earth,

$x =$ distance from apex,

$d =$ distance between cone and earth measured along the circular arc.

$$\therefore\ d = ax.$$

The length of the magnetic path is $2\pi x$, and the flux per

radial centimetre for unit current is $\frac{4\pi d}{2\pi x} = 2a$. The inductance per radial centimetre is, therefore, constant, and equal to $2a \times 10^{-9}$ henries.

The capacity per radial centimetre is $\frac{2\pi x}{4\pi d} = \frac{1}{2a}$ absolute units, or $\frac{1}{2a \times 9 \times 10^5}$ microfarads.

The strength of the electric field E at any point is given by dividing the P.D. between the cone and earth by the distance between them. As the P.D. is constant for a transmission line of this nature as shown on page 41, the electric field strength evidently varies inversely as the distance from the centre.

Similarly, since the length of the magnetic path varies inversely as the distance from the centre, the magnetic field strength must vary accordingly.

The electromagnetic waves propagated in this manner are not plane waves but spherical, as their wave fronts are approximately spheres.

It will be seen that the copper cone and the surface of the earth merely act as guides for the electromagnetic waves in the ether. The waves themselves are due to the simultaneous presence of electric and magnetic fields. Any change in the strength of the electric field is accompanied by a change in the current flowing along the two guides, and at any instant the electric field forms loops of force which are completed through the guides. Now, if Maxwell is correct regarding his assumption that a change of electric flux is equivalent to a current, it would appear possible for the loops of force to be completed through the dielectric if there were no guides. The propagation of electromagnetic waves would thus appear to be possible without the copper cone once the necessary electric and magnetic fields are produced near the alternator.

The electric field would then take the form shown in Fig. 32, owing to the repelling action of adjacent lines of force.

The magnetic field is present as before, at right angles to the electric field and in phase with it. Near the small portion of the copper cone, or aerial, left at the alternator to produce the necessary fields, the conditions will be rather more complicated, as there will now be oscillating fields due

to wattless currents in the aerial in addition to the fields producing the radiated energy.

From the above it would appear possible theoretically to transmit energy through the ether in the form of electromagnetic waves, and Maxwell came to a similar conclusion as a result of his electromagnetic theory of light. Subsequent experience has confirmed his predictions. Maxwell, however, did not consider the surface of the earth as forming one plate of the condenser or transmission line, and it was not until Marconi discovered the possibility of this substitution that the transmission of electromagnetic waves for purposes of wireless telegraphy became practicable.

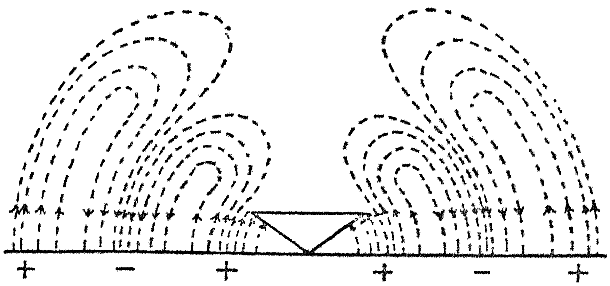


Fig. 32.

Maxwell calculated, and experiments have since shown, that the velocity of electromagnetic or light waves through any medium should be equal to $\frac{1}{\sqrt{\kappa\mu}}$ cm. per second, where κ is the specific inductive capacity of the medium, and μ is the permeability. κ and μ have not yet been determined absolutely, but are always determined relative to the values of κ and μ for air. κ is taken as unity for air in the electrostatic system of units, and μ is taken as unity for air in the electromagnetic system of units.

The formula, velocity $= \frac{1}{\sqrt{\kappa\mu}}$, is similar to the formula for other forms of wave-motion, viz. velocity $= \sqrt{\frac{\text{elasticity}}{\text{density}}}$,

where μ corresponds to density, and $\frac{1}{\kappa}$ corresponds to elasticity. For air or a vacuum $\kappa = 1$ measured in electrostatic units, and $\mu = 1$ measured in electromagnetic units, and the ratio of the two sets of units is 3×10^{10} cm. per second, which is the velocity of light and electromagnetic waves in the ether, so for any medium velocity $= \frac{3 \times 10^{10}}{\sqrt{\kappa\mu}}$ cm. per sec.

22. Hertzian or Dumb-bell Oscillator.—Although Maxwell's paper, dealing with his electromagnetic theory, was published in the year 1865, it was not until 1888 that anything was published dealing with the practical side of the question.

In 1888 Hertz published an account of his experiments on the production, transmission, and detection of electromagnetic waves. His radiating oscillatory circuit consisted of two metal plates connected to the spark gap of an induction coil. The capacity between the two plates and the inductance of the connections between them formed the necessary capacity and inductance for the oscillatory circuit (Fig. 33). This type of radiator or oscillator is known as the **linear** or **dumb-bell** type.

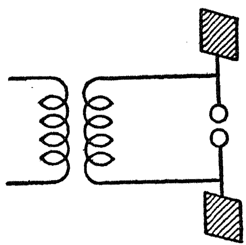


Fig. 33.

Hertz devised a **resonator** of the form shown in Fig. 34 for detecting the waves. This consisted of an almost complete loop of wire whose ends formed a spark gap. He discovered that when the resonator was held in certain positions relative to the oscillator a spark passed across the spark gap of the resonator.

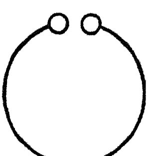


Fig. 34.

Thus the existence of electromagnetic waves came to be acknowledged as the result of both theoretical and practical investigation, and experiments were carried out by numerous investigators who realised the practical value of these waves for signalling purposes.

23. Plain Aerial Oscillator.—About 1895 Marconi made an important discovery which made electromagnetic waves of commercial value. He discovered that if one of the spark gap terminals of the induction coil used in Hertz's arrangement were connected to a plate buried in the ground the surface of the earth could be used as one plate of the condenser; and also that the higher the other plate was above the ground the greater was the distance over which he could transmit electromagnetic waves. He found that an actual plate was unnecessary, and that a vertical wire supported by a kite or masts gave similar results, the capacity in this case being distributed along the wire. It was found better, however, to use a number of wires in parallel for the upper portion of the aerial in order to increase the capacity for transmission on longer wave-lengths.

It will be appreciated that it is necessary for the aerial circuit to be tuned to the required wave-length to give maximum current and voltage, in order to produce magnetic and electric fields of the greatest possible strength with a given power supply. In addition, the resistance of the aerial must be kept as low as possible to prevent useless dissipation of energy.

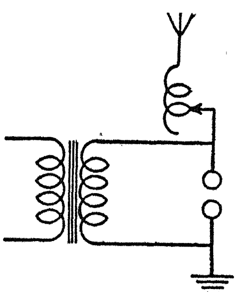


Fig. 35.

Marconi used an arrangement similar to that shown in Fig. 35 for his early experiments.

One terminal of the spark gap of an induction coil was connected through a variable inductance to a vertical wire, and the other terminal of the spark gap was connected to a plate buried in the ground. The variable inductance enabled the aerial circuit to be tuned to various wave-lengths. Such a circuit caused the aerial oscillations to be heavily damped, on account of the resistance of the spark gap, and consequently highly damped electromagnetic waves were transmitted. In addition the tuning was flat, and the waves transmitted were consequently liable to cause interference on wave-lengths other than their own intended wave-length. An arrangement of this kind was called a **plain aerial.**

An improvement was made by making the aerial circuit a coupled circuit and using loose coupling, as shown in Fig. 36.

Spark methods of producing electromagnetic waves still use circuits of this nature, which is a decided improvement on the plain aerial method, but the tuning is still flat, and highly damped waves are radiated. If the coupling is too tight, waves of two frequencies are radiated, as shown in Chapter I.

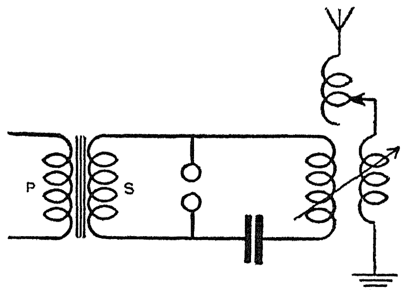


Fig. 36.

24. Effect of Electromagnetic Waves on a Vertical Wire or Loop.—Provided no distortion of the electromagnetic waves occurs in their passage over the earth, the electric field due to them at any point on the surface of the earth will be approximately vertical, and the magnetic field will be approximately horizontal and at right angles to the direction of the transmitting station.

It is obvious, therefore, that the presence of the waves can be detected by utilising either the electric field or the magnetic field.

A vertical wire will be affected by the electric field, and will have charges induced on it, thus producing an oscillatory current in it.

A closed vertical loop will have currents induced in it by the magnetic field, except when its plane is at right angles to the direction of the transmitting station. The induced currents will be a maximum when the plane of the loop or coil is in the direction of the transmitting station. The possibilities of a rotating loop of this nature for determining the direction of a transmitting station will be realised. (See Chapter IX.) The E.M.F. induced in the loop may be calculated in terms of the magnetic field, or in terms of the electric field, the same result being arrived at in each case. (See page 176.)

In many cases the wave front is not vertical on account of

several reasons (see page 49), but there will always be a vertical component of the electric field and a horizontal component of the magnetic field if the wave is travelling along the surface of the earth. E.M.F.'s will therefore be induced in a vertical wire or loop, provided the plane of the latter is not parallel to the wave front, even under these conditions, and as there will be a horizontal component E.M.F.'s may even be induced in a horizontal wire if this component is sufficiently strong.

If the vertical wire is connected to earth through a variable inductance, a complete circuit is formed through the wire, inductance, and the capacity between the wire and earth (Fig. 37 (*a*)). By tuning this circuit to the wave-length of the electromagnetic waves to be received, the induced E.M.F.'s may be made to produce comparatively large E.M.F.'s across the inductance, and comparatively large currents through it provided the resistance or damping of the circuit is small. These E.M.F.'s or currents can then be detected by suitable apparatus. The circuit can also be tuned by putting a variable condenser across the inductance, *i.e.* in parallel with the capacity to earth (Fig. 37 (*b*)), or in series as Fig. 37 (*c*).

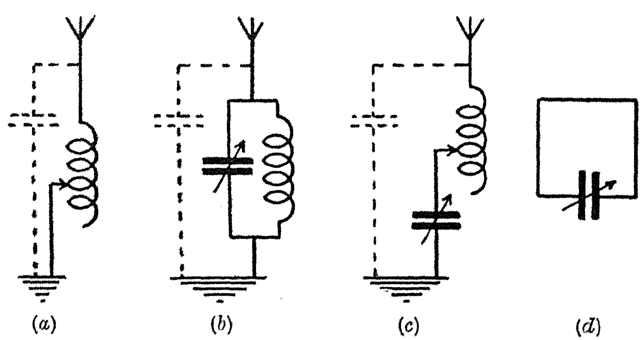
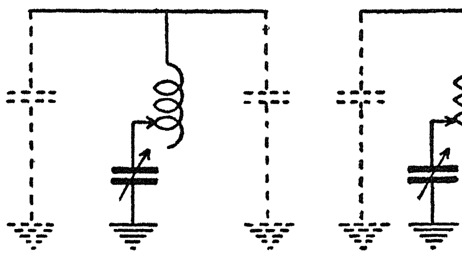


Fig. 37.

Similarly, a variable condenser may be connected in series with a loop, and a tuned circuit formed in this manner (Fig. 37 (*d*)).

In practice it is usually difficult to erect a vertical wire without its being close to an earthed support, the capacity to which would provide a large leakage of the induced currents, so a more or less horizontal wire, connected to the receiving apparatus at either the middle or one end, is very often used (Fig. 38).

Different kinds of aerials are discussed more fully in Chapter X.



(a) (b)

Fig. 38.

25. Effect of the Earth on Electromagnetic Waves.— So far in this chapter the surface of the earth has been treated as a perfect conductor for purposes of explaining the nature of electromagnetic waves in the ether. Actually, however, the conductivity of the surface of the earth varies a great deal, depending on its nature.

Sea water is a very good conductor, but dry soil is a very bad conductor. It is evident, therefore, that the currents flowing in the surface of the earth, which accompany the electromagnetic waves, must dissipate energy, the amount dissipated depending on the nature of the surface of the earth over which the waves travel.

This energy must be supplied by the waves themselves, consequently the wave front cannot remain vertical, but becomes slightly tilted in order that energy may be transmitted vertically into the earth as well as horizontally along its surface.

This can easily be seen if it is remembered that the direction of the transmission of energy is at right angles to both

the electric and magnetic fields. If energy is to be transmitted into the earth the electric field must have a horizontal component, and the magnetic field must have a component parallel to the direction of the wave. These conditions can only be obtained by the wave front becoming tilted in the direction of travel.

It is evident that transmission of electromagnetic waves can be carried out over the sea for much greater distances than over land, especially dry land.

The greater the frequency of the waves the greater will be the losses, consequently long waves are preferable in this respect for long distance transmission.

The effect of this tilting of the wave front is to make the waves tend to follow the curvature of the earth instead of travelling off into space.

If the surface of the earth is hilly or woody in the vicinity of a receiving aerial, the electric field in which the aerial is situated may become almost horizontal, and the major portion of the energy available in that part of the wave front may be dissipated. Consequently reception is very poor under these circumstances, and the aerial is said to be **screened.**

26. Effect of the Atmosphere on Electromagnetic Waves.—In the preceding section it has been shown how some of the energy of the electromagnetic waves travelling over the surface of the earth is dissipated in the resistance of the earth, owing to the surface of the earth not being a perfect conductor. Similarly energy is dissipated in the atmosphere owing to the latter not being a perfect dielectric. It was shown also how the dissipation of energy in the earth assisted the waves in following the curvature of the earth. Mathematical investigation of the effect of the earth shows, however, that this is not sufficient to account for the long ranges obtained in actual practice; it has been necessary, therefore, to attempt to account in some other way for the results obtained practically.

Considering once more the transmission of electromagnetic waves between two conductors, it is obvious that if the earth were surrounded by a spherical conductor some distance away from it the waves would be confined between this

conductor and the surface of the earth, and would thus follow the latter until all the energy was dissipated.

It is believed that such a conductor actually exists, and it is known as the **Heaviside layer** after the scientist of that name who has done a great deal of work in the mathematical investigation of electromagnetic waves, and who suggested its existence.

The Heaviside layer consists of a shell of ionised air which acts as a very good conductor. This upper layer of air is thought to be ionised by ultra-violet rays of light from the sun, which, on account of their high frequency, are largely absorbed before they reach the lower atmosphere. Partial ionisation occurs, however, in the lower atmosphere and causes dissipation of energy.

During the night most of the ions in the lower atmosphere combine, and less energy is absorbed from the waves as a result, thus enabling longer ranges to be obtained at night than in the daytime. Irregular masses of ions, however, may not combine owing to local conditions, and consequently irregular results may be obtained; also sudden combinations may occur, due to moving masses of ions approaching each other, and thus cause electromagnetic disturbances in the atmosphere which affect the receiving apparatus, and are known as **atmospherics** or **strays** or **"Xs."** These occur to some extent during the day, but not so much as at night for the above reason.

During the day short waves, *i.e.* waves of high frequency, obviously suffer more dissipation of energy than longer waves, and have consequently a shorter range for the same power radiated from the transmitting aerial. At night the difference between short and long waves is not so marked, and recent results show that short wave wireless telephony is possible at night over a range of several thousands of miles with a power of only a fraction of a kilowatt.

It has been noticed that signals at a receiving station often die away and then return to normal strength without any change in adjustments at either the receiving station or the transmitting station. This peculiarity is known as **fading** and is believed to be the result of reflection of the waves at the Heaviside layer. When reflection occurs both the reflected wave and the wave received direct may be

received by the same station, and, as they have travelled different distances, they will be out of phase and will, therefore, reduce the strength of the signals.

Communication between two stations, one of which is situated in a part of the globe where it is night-time, and the other is situated where it is day-time, is usually difficult. This is probably due to reflection and diffusion in the zone where the change from darkness to light occurs, owing to the irregular ionisation in this zone.

CHAPTER III.

DETECTION OF ELECTROMAGNETIC WAVES.

27. Introductory.—It has been shown in the preceding chapters how electromagnetic waves, produced by high frequency oscillating currents in the transmitting aerial circuit, are capable of inducing oscillatory currents of the same frequency in an aerial situated at a distance from the transmitting aerial.

As the oscillatory currents induced in the receiving aerial are of very small magnitude, and of too high a frequency to be detected by ordinary methods of detecting or measuring low frequency alternating currents, special methods of detecting them are necessary.

The range over which electromagnetic waves can be transmitted and received with certainty depends primarily on the amplitude of the transmitted waves, and on the sensitivity of the detecting apparatus. Consequently the more sensitive the detector can be made the smaller will be the power required at the transmitting station.

Thermo-electric methods are used for *measuring* high frequency currents, but other methods are more sensitive and much simpler for *detecting* purposes.

The Hertz Resonator employed by Hertz for demonstrating that electromagnetic waves could be detected at a distance from his oscillator, is not suitable for working over more than a very short distance.

In order to cause a visible spark to pass across a spark gap at least 300 volts are required across the gap; consequently the Hertz resonator, even when adjusted to have a natural frequency equal to that of the electromagnetic waves to be received, is far from being a sensitive detector.

28. Requirements of a Detector.—It has been shown in Chapter II. how the magnitude of the high frequency E.M.F.'s or currents induced in the receiving aerial can be increased by using a large aerial, and by tuning the natural frequency of the aerial to that of the waves to be detected. Once these E.M.F.'s or currents have been set up some suitable apparatus is required to enable them to produce an effect which can be detected by the senses.

In order that electromagnetic waves can be used for signalling purposes, it is necessary that any starting and stopping of the current in the transmitting aerial, or any change in magnitude or frequency of this current, whichever the operator at the transmitting station desires to control, should be faithfully reproduced at the receiving station in some form perceptible to a person at this position. The method adopted for affecting the senses of the receiving operator can be one which enables him to perceive the signals as they are received, or can be one which records the signals in some form suitable for the operator to interpret at leisure if he desires. The most suitable method of the former class is one appealing to the ear, as in ordinary line telegraphy, such as a telephone or sounder. An example of the latter class is a tape machine or a Morse inker, which can also be of the former class provided the rate of working is not too great.

It will be seen, therefore, that some means are necessary for producing unidirectional currents or currents of comparatively low frequency at the receiving station, in order to actuate something of the nature of a telephone or a Morse inker. If the frequency is too high, as in the case of oscillatory currents used for wireless telegraphy, these instruments will fail to respond, and, even if the frequency is low enough to actuate a telephone, for instance, the frequency must be within the comparatively low limits of audibility.

The fundamental requirement of a detector of high frequency oscillatory currents for signalling purposes is, therefore, that it must be capable of producing unidirectional or low frequency currents, which vary as the high frequency oscillations in the receiving aerial vary. The various kinds of detectors which have been used for this purpose are described in the present chapter.

29. Filings Coherer.—The detection of electromagnetic waves was first made a success for signalling by wireless telegraphy by Marconi, who developed the filings coherer. This method is now obsolete, but it was due to it that wireless telegraphy became a commercial success.

For some time before Marconi carried out experiments on the detection of electromagnetic waves it was known that when a large electromotive force was applied to certain partially conducting substances, such as fine metal filings, or loose metallic powders, the conductivity of these substances increased.

Professor Branly, of Paris, discovered that a spark at a distance from a loose metallic powder increased the conductivity of the latter, although in some cases, *e.g.* in lead compounds, he discovered that the conductivity decreased. He and other investigators tried different kinds of metal filings in loose contact, and found that they were extremely sensitive to the passage of a distant spark.

It was some time before it was realised that the change in the conductivity was due to electric radiation and not to the light of the spark. In 1894 Sir Oliver Lodge publicly demonstrated that the conductivity of loosely packed iron filings, contained in a glass tube closed by a metal plug at each end, was increased when electric radiation fell upon it, and he gave the name **coherer** to any device of this nature.

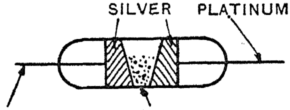


Fig. 39.

During the next few years Marconi developed the filings coherer and auxiliary apparatus, and took out patents in England. His coherer consisted of a mixture of very fine silver and nickel filings between two polished silver plugs, the whole being enclosed in an exhausted glass tube about $1\frac{1}{2}$ inches long and about $\frac{1}{4}$ inch internal diameter (Fig. 39). Contact with the silver plugs was made by means of platinum wires sealed through the glass. The gap between the plugs was made wedge-shaped, so that the sensitivity could be altered by altering the position of the filings. The resistance of a coherer of this nature may be as large as

several million ohms, but may be as low as 10,000 ohms. If the P.D. is increased sufficiently the resistance falls to a few ohms.

Dr. Eccles put forward the theory that the decrease in resistance is due to local heating at the points of contact of the filings, which forms films of oxides with a negative temperature coefficient. There is, however, no generally accepted explanation.

Marconi further developed means of restoring the coherer to its sensitive condition, and for using it to record signals sent by wireless telegraphy. He used an electromagnetic

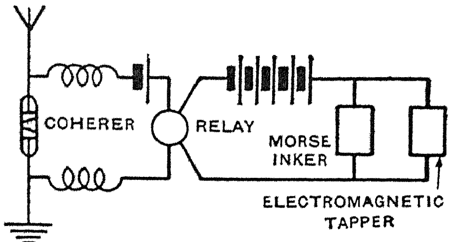


Fig. 40.

tapper which tapped the coherer constantly to restore it to a sensitive condition, and this was connected in parallel with a Morse inker operated by a relay. The relay was actuated by the current through the coherer (Fig. 40).

Marconi's coherer method with Morse inker gave excellent results in skilled hands, but it required delicate adjustment and was soon replaced by the magnetic detector.

30. Magnetic Detector.—An oscillatory current passing round an iron core appears to have the same effect as hitting the iron core with a hammer, that is to say the molecules are freed from restraint and are free to be magnetised or demagnetised: in other words, the hysteresis effect is eliminated. This is the explanation advanced for the action of the **magnetic detector** devised by the Marconi Company from experiments by previous investigators such as Henry and Rutherford.

In the Marconi magnetic detector (Fig. 41 (*a*)) an iron band composed of fine, insulated iron wires is slowly moved by clockwork through a magnetic field. The iron wire is magnetised and tends to remain magnetised as it leaves the magnetic field.

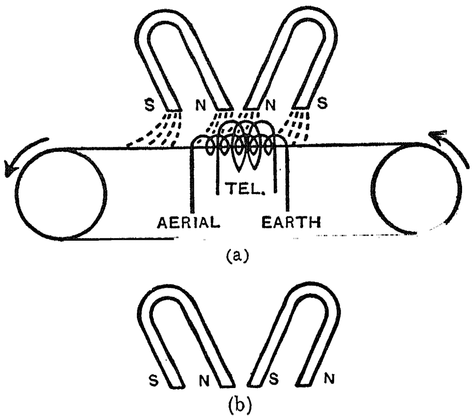


Fig. 41.

Surrounding the iron wire in the magnetic field is a coil carrying the high frequency oscillations to be detected. Each time a group of oscillations passes through this coil there is a change of flux through the iron wire, as any remanent magnetism is partially wiped out. The change of flux causes a click in a telephone connected across another coil wound over the coil carrying the oscillations; consequently a note is heard in the telephones, its frequency being equal to the frequency of the groups of oscillations, *i.e.* equal to the spark frequency. The spark frequency must not be too high, otherwise the strengths of successive clicks are not the same, as a fresh portion of iron wire has not reached the magnetic field.

Owing to irregularities in the iron band noises are heard in the telephone even when no oscillatory current is passing. This has been decreased by reversing one of the magnets, as shown in Fig. 41 (*b*).

The magnetic detector replaced the coherer, and was the usual detector fitted on ships at one time. It was superseded by the crystal detector, which was later superseded by the valve detector for most purposes.

31. Electrolytic Detectors.—Various forms of **electrolytic detectors** have been tried, but they have never been really serious rivals to other kinds of detectors.

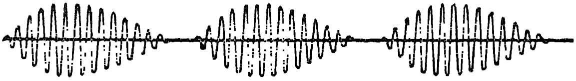
In one form of electrolytic detector a fine platinum wire is coated with silver or nickel and drawn out. The silver or nickel is then dissolved by acid and a fine platinum wire of microscopic dimensions left projecting from a glass tube. This, together with a piece of platinum foil or wire, is placed in dilute sulphuric acid, the fine platinum wire being used as the positive electrode where oxygen is given off.

When the difference of potential across the electrodes is increased polarisation prevents much current flowing until a certain value of the P.D. is reached. If a high frequency oscillation is applied a large current flows, and can be used to affect a telephone connected in series. This electrolytic detector very quickly recovers, and can be used for high frequencies. It is affected by an amplitude of one ten-thousandth of a volt.

32. Rectification of High Frequency Oscillatory Currents.—The oscillatory current set up in a receiving aerial is of the nature shown in Fig. 42 *(a)*, when the oscillations in the transmitting aerial are caused by discharges across a spark gap.

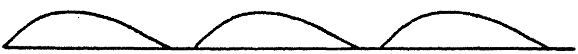
If a suitable rectifier is introduced into the circuit, *i.e.* some instrument that will allow current to pass in one direction only, the high frequency current passing through the rectifier will be unidirectional, as shown in Fig. 42 *(b)*. The effect of this high frequency unidirectional current on a telephone, or other instrument possessing inductance, which is short-circuited by a condenser to allow the high frequency rectified current to pass, is to produce a unidirectional current which passes through the instrument each time a group of oscillations is set up in the receiving aerial, *i.e.* each time a spark passes at the transmitting station. The note heard in the telephone will, therefore, be of the same frequency as the

frequency of the spark. Hence, whenever oscillations are being set up in the transmitting aerial a note is heard in the telephone at the receiving aerial. This note will start and stop as the operator at the transmitting station starts and stops the supply to the spark gap; consequently intelligible signals can be transmitted and received as in line telegraphy.



(a)

(b)



(c)

Fig. 42.

(*a*) Oscillations in Receiving Aerial. (*b*) Rectified oscillations.
(*c*) Current through Telephone.

If the electromagnetic waves employed are undamped or continuous, as produced by an arc, some means must be adopted to stop and start them, or change their amplitude, at an audible frequency in order to produce a note in the telephones, otherwise the result would be simply a steady current passing through the telephones; the only indication that waves were being sent out would be a slight click in the telephones each time the transmitting key was pressed and released.

Either the undamped oscillations at the transmitting station or those set up at the receiving station can be varied at an audible frequency; the result in each case is to provide a note of the same frequency in the telephones.

The methods used are described in other chapters, but, as the received oscillations have to be rectified in the same way as those caused by damped oscillations in the transmitting aerial, the consideration of rectifiers in the present chapter

applies to the reception of both damped and undamped electromagnetic waves.

Any conductor acts as a rectifier if its characteristic curve showing the relation between current and P.D. has a pronounced curvature. Fig. 43 shows a characteristic curve of this type.

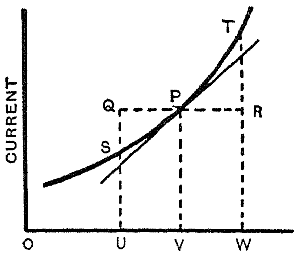


Fig. 43.

If OV represents the normal P.D. across the conductor then an increase equal to VW will cause the current flowing to increase from VP to WT, *i.e.* the increase in current will be RT. An equal decrease in the P.D. will decrease the current flowing by an amount QS.

Owing to the shape of the curve the increase RT is greater than the decrease QS, consequently an oscillatory P.D. applied across the conductor would cause an oscillatory current to be superimposed on the steady current flowing through the conductor, the value of the oscillatory current being greater in one direction than the other. The result of this is to produce a unidirectional or rectified current whose value varies at the same frequency as the incoming electromagnetic waves (Fig. 44).

If P represents the normal conditions at the rectifier, the effect of the oscillatory P.D. shown is to cause the current through the rectifier to be of the form shown. If the rectified current passes through a condenser connected across a telephone, the resultant charge on the condenser causes a unidirectional current to flow through the telephone. Rectifiers of this nature are the **crystal and valve detectors** described on subsequent pages.

It will be seen from Figs. 43 and 44 that the greater the amplitude of the high frequency oscillations the greater in proportion will be the rectified current, as the excess of current in one direction over that in the other direction increases as the amplitude increases owing to the shape of the characteristic curve. Consequently rectifiers with characteristic curves of this nature are more efficient for strong signals than for weak signals.

33. Crystal Detectors.—When certain crystalline minerals are placed in contact with certain metals or other minerals the resistance of the contact does not behave in accordance with Ohm's law. The characteristic curve of the combination, showing the relation between current and P.D., has a pronounced curvature, and, therefore, the combination acts as a rectifier as described on preceding pages. Carborundum, silicon, and pyrites in combination with a metal

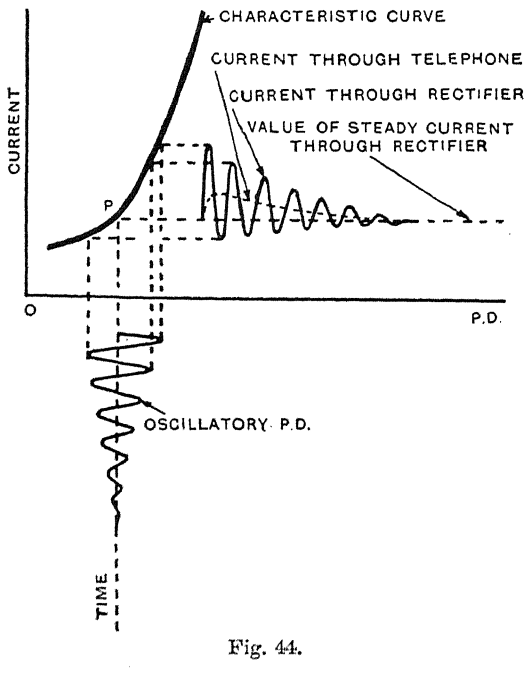


Fig. 44.

all have rectifying properties, and various combinations of such mineral ores as bornite, copper pyrites (chalcopyrite), zincite, and molybdenite have similar properties.

Crystal detectors sold under various trade names are usually combinations of the above substances. The com-

binations which have been found to be most satisfactory for use in wireless telegraphy are carborundum and steel, zincite and chalcopyrite, and zincite and bornite. A combination which includes zincite is often called a **Pericon detector.**

A fragment of the mineral ore, usually referred to as the crystal, is generally mounted in a small brass cup and secured in place by solder. The other member of the combination is kept in contact with it by means of an adjustable spring, and the point of contact can be altered by rotating the crystal.

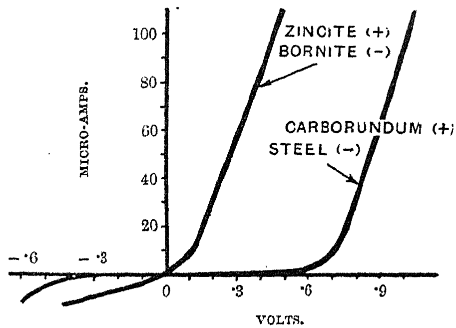


Fig. 45.

Some crystals require careful adjustment of the contact pressure and of the point of contact to give satisfactory results, and are easily thrown out of adjustment by extra strong signals or vibration. Carborundum is one of the most robust and stable crystals, but it has the disadvantage that a small dry battery and potentiometer are required to give the necessary P.D. to enable the detector to work on the most sensitive portion of the characteristic curve (see Fig. 45). The potentiometer is usually wired so that either a positive or a negative P.D. can be applied.

Some other crystal detectors are more sensitive if a potentiometer is used, but give good results without one, and are often used without one for the sake of simplicity.

It will be seen from Fig. 45, which shows typical characteristic curves, that a P.D. of about 0·6 volts is required for sensitive working in the case of the carborundum-steel

detector, but that no potentiometer is required for zincite-bornite.

Although a large amount of work has been carried out in investigating the properties of crystal detectors, the reasons for the curved characteristics of these detectors is not fully understood. Thermo-electric effects undoubtedly play an important part, as pointed out by Eccles and Owen. (See *Proceedings Physical Society, London,* June 1913—"On Electrothermal Phenomena at the Contact of Two Conductors," by W. H. Eccles, and *Proceedings Physical Society, London,* June 1916—"The Laws of Variation of Resistance with Voltage at a Rectifying Contact of Two Solid Conductors, with Application to the Electric Wave Detector," by D. Owen.)

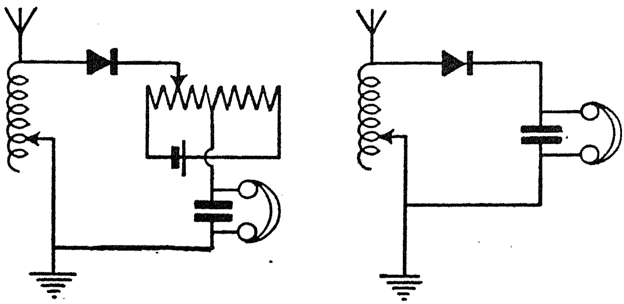


Fig. 46.

As the crystals are bad conductors of heat, and have usually a negative temperature coefficient, the passage of a current causes local heating at the contacts and a change in the resistance. In addition there is a Peltier effect when two different substances are used, which assists the voltage in one direction and opposes it in the other direction.

Crystal detectors have been largely superseded by valve detectors, but the introduction of broadcast wireless telephony has revived their use for short range reception, as they are simple and cheap, and fairly reliable even in unskilled hands.

It will be seen from Fig. 45 that the resistance of a crystal detector is of the order of thousands of ohms, consequently a crystal detector cannot be connected in series with the aerial, but must be connected in parallel with the main oscillatory path so that maximum P.D. is applied to the detector.

Fig. 46 shows one method of connecting up a crystal detector, both with and without a potentiometer, for the detection of electromagnetic waves. Other methods are shown on pages 66 to 68.

On account of the high resistance of a crystal detector high resistance phones must be used in series for best results. Usually each earpiece has a resistance of about 4,000 ohms, giving a total resistance of 8,000 ohms. (See page 69).

34. Valve Detectors.—If the two electrodes of a vacuum tube are connected to a source of E.M.F. no current will pass through the tube if the E.M.F. is below a certain value. If, however, one of the electrodes is made incandescent, the E.M.F. required to cause a current to flow through the vacuum tube is very much reduced. Current flows, however, only when the negative terminal of the source of E.M.F. is connected to the incandescent electrode. If the E.M.F. is reversed no current will flow. A vacuum tube of this nature therefore acts as an electrical valve, and was called an **oscillation valve** by J. A. Fleming, who was the first to use this method for rectifying high frequency oscillations. He took out a patent in 1904 for this method of detecting wireless signals.

Fleming used a carbon filament, kept incandescent by a battery, as the incandescent electrode, and a metal plate or cylinder as the cold electrode or anode. He connected the two electrodes through a telephone to the high frequency E.M.F. to be detected. It will be noted that this method uses the *non-return properties* of the vacuum tube.

An oscillation valve, or **thermionic tube,** as it is often called, has a characteristic curve similar to that of a crystal. In consequence this property can also be utilised for the rectification of electric oscillations. Fleming took out a patent for this method in 1908, and found that a tungsten filament was better than a carbon filament.

As in the case of the carborundum crystal, it is necessary to supply a steady P.D. in order to work on the correct portion of the characteristic curve, but in the case of the Fleming valve the P.D. required varies from 50 to 100 volts, whereas the carborundum crystal requires only 0·6 volts. One method of connecting up a two electrode valve for use in this manner is shown in Fig. 47.

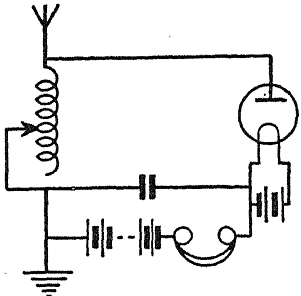


Fig. 47.

The Fleming valve was not quite so sensitive as a good crystal detector, but was more stable and, therefore, largely used.

The introduction of a third electrode into the electric valve, by Lee de Forest in 1907, increased its sensitivity enormously, and has enabled it to be used for all kinds of purposes. The third electrode is usually a wire grid placed between the filament and the cold electrode, which is usually referred to as the anode. One method of connecting up the three electrode valve, or **triode,** as it is often called, is shown in Fig. 48.

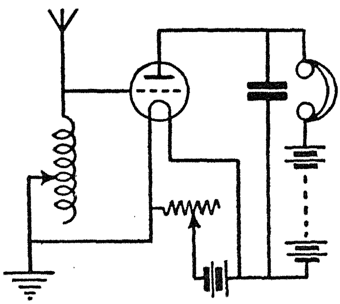


Fig. 48.

The oscillatory P.D. between the grid and the filament causes a corresponding variation in the direct current flowing between the anode and filament. The change in the direct current is, however, much greater than with the two electrode valve. A potentiometer or other means is usually required to maintain the grid at the correct potential relative to the filament for most effective working.

The theory and construction of the thermionic valve is dealt with more fully in Chapter V.

A type of valve which uses a liquid electrode of sodium as the anode has recently been invented in America, and is claimed to be a highly efficient detector. The nature of this type of valve is indicated in Fig. 49. The sodium is heated by means of a heater in series with the filament in order to cause ionisation. A "collector" electrode of sheet metal bent towards the anode is suspended above the filament, and is kept at the required potential by a potentiometer across the filament battery. The valve is connected to the receiving circuit in the same way as an ordinary three electrode valve detector, the collector electrode taking the place of the grid in the ordinary three-electrode valve.

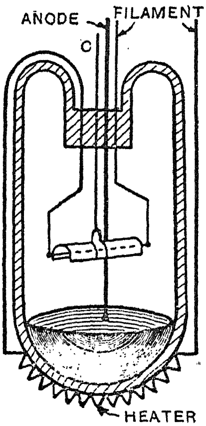


Fig. 49.

35. Simple Receiving Circuits.—Various methods of detecting high frequency oscillations produced in an aerial circuit by electromagnetic waves have been considered. Simple detection, however, of electromagnetic waves is not all that is required when electromagnetic waves are being used for communication purposes.

For satisfactory reception of signals the following are the main requirements:—

(*a*) The high frequency oscillations to be detected should be large enough to produce strong signals in the telephones or other apparatus.

(*b*) Electromagnetic waves of a frequency other than that of the waves it is desired to receive should not affect the detector.

Both these requirements are largely met by tuning the aerial circuit to the required wave-length, but the detector should be so connected that the damping of the circuit is kept small, otherwise the induced oscillations are of small magnitude and the resonance curve of the circuit is flat topped.

It is obvious, therefore, that a high resistance detector must not be connected directly in the path of the oscillatory current. It must be connected so that a large P.D. is applied to it without seriously increasing the damping. A simple method is shown in Fig. 50.

The aerial circuit is tuned by means of the variable aerial tuning inductance, and the tapping point for the detector can be adjusted for maximum efficiency. The higher the resistance of the detector the higher will be the tapping point required to keep the damping to a minimum.

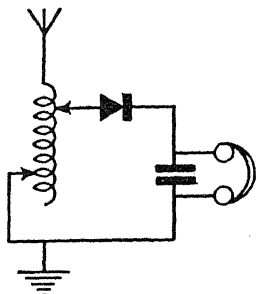


Fig. 50.

It is not always possible to have an aerial tuning inductance of a large enough value to give the best tapping point. This can be overcome by introducing an additional tuned circuit L_2C_2 (Fig. 51) coupled to the aerial circuit. L_2 and C_2 can

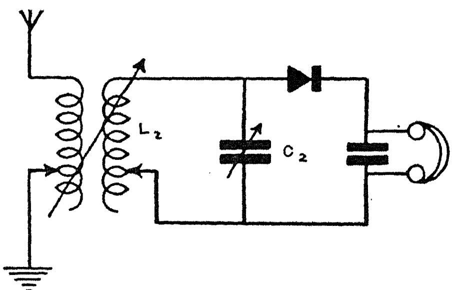


Fig. 51.

be so adjusted that the damping of the secondary circuit is very small, and thus gives sharper resonance than would be obtained with the detector connected directly to the aerial circuit which has a larger damping coefficient. (See Chapter I.)

If still greater selectivity is required another coupled circuit can be introduced as shown in Fig. 52, but this is not usually necessary.

Fine tuning is usually carried out by means of a variable condenser instead of a variable inductance. The aerial tun-

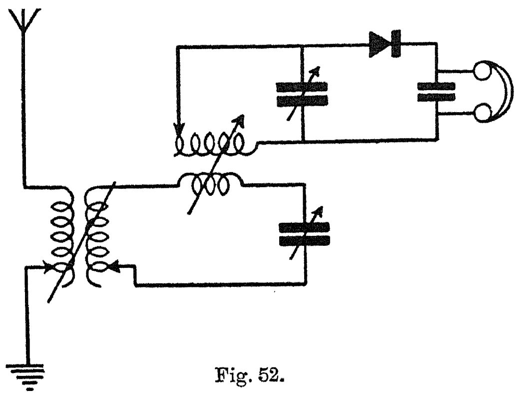


Fig. 52.

ing condenser may be connected in parallel with the aerial tuning inductance or in series, either on the aerial side or the earth side. (See Fig. 53.)

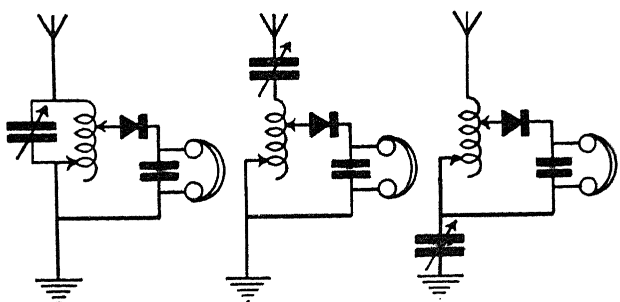


Fig. 53.

The impedance of the telephones should be high when used with a detector of high resistance, as the current is small and more turns are required to give the necessary number of ampere-turns.

In order to avoid the use of fine wire required to construct high impedance telephones, which causes the resistance to be several thousand ohms, a step down transformer is often used with low impedance telephones of about 120 ohms resistance.

The two kinds of telephones are usually referred to as "high resistance" telephones and "low resistance" telephones. High resistance telephones are liable to be damaged by the steady current which flows when a potentiometer is used with a crystal, and more especially in the case of valve detectors, where the steady current is larger.

Receiving circuits are discussed more fully in Chapter VI.

36. Continuous Wave Reception.—As stated on page 59, undamped or continuous high frequency oscillations require to be broken up at an audible frequency to enable a note to be heard in the telephones. Various mechanical methods have been tried, *e.g.* the "tikker" method, but they have all been superseded by the **heterodyne method,** due to Fessenden (1902).

The heterodyne method consists of combining the incoming high frequency oscillations with locally produced high frequency oscillations of slightly different frequency. The result is to produce an oscillatory current whose frequency is equal to the difference between the frequencies of the two sets of oscillations, as in the case of beats in sound (see pages 27, 30). The resultant current can then be detected by the methods already described.

CHAPTER IV.

THE PRODUCTION OF HIGH FREQUENCY OSCILLATORY CURRENTS.

37. Comparison of Damped and Undamped Waves.—In Chapter I. it is shown how damped oscillatory currents can be produced by means of a spark gap, and how undamped oscillatory currents can be produced by means of an arc or a high frequency alternator.

The various methods of producing high frequency oscillatory currents are evidently of two classes, viz. those which produce damped oscillatory currents, and those which produce undamped oscillatory currents. The latter class includes methods of producing oscillations which are continuous, or similar to ordinary low frequency alternating currents, and also includes methods whereby the undamped oscillations are interrupted, *i.e.* started and stopped, at a regular rate. Methods of the latter kind are referred to on page 59 as a means of producing electromagnetic waves which can be received by simple methods of detection.

All modern stations are being fitted with continuous wave systems of producing high frequency oscillatory currents, mainly on account of the following advantages of continuous waves over damped waves :—

(*a*) Lower voltages are required in the aerial for the radiation of the same power, owing to the transmission being continuous all the time the transmitting key is pressed, instead of having dead spaces between successive trains of oscillations as in the spark system. This reduces losses due to brush discharge and leakage and requires less insulation, but suitable material such as porcelain must be used for the insulators, otherwise the continuous strain causes decomposition of insulators which may be able to withstand the

higher but less frequently applied voltages of the spark system.

(*b*) Greater selectivity is possible owing to the sharper tuning, which causes the energy to be radiated at one wave-length only, apart from a very small percentage radiated by harmonics. The flat tuning with spark systems causes interference on wave-lengths differing quite a lot from that to which the system is tuned.

(*c*) Less absorption is experienced with continuous waves over long distances.

(*d*) More sensitive receiving apparatus can be employed, and the pitch of the note of the signal heard by a receiving operator can be controlled to make it distinguishable from interfering noises such as atmospherics, etc., and to suit his ear.

38. Methods of Producing Damped Oscillations.—The various methods of producing damped oscillatory currents depend on some means of regularly charging up a condenser and discharging it round an oscillatory circuit. The required object can be achieved by some kind of mechanical make and break which automatically charges and then discharges the condenser, or a spark gap can be used as described in Chapter I.

If a mechanical make and break is used, *e.g.*, a revolving commutator, or a buzzer, sparking occurs at the contacts and the method becomes the same in principle as the rotary spark gap. (See page 77.)

Spark gap methods are responsible for the production of practically all damped oscillatory currents used for wireless telegraphy and telephony, and it is only comparatively recently that spark transmitters have begun to be superseded to any great extent by continuous wave transmitters.

39. Spark Gap Methods Using Direct Current.—Various methods of setting up oscillations in an oscillatory circuit by regularly charging and discharging a condenser from a direct current supply have been tried. Most of these methods are only suitable for low powers on account of various difficulties, such as the difficulty of obtaining high

voltage direct current supplies, compared with high voltage alternating current supplies.

The following are methods still in use, the latter being the only one used for large powers :—

(*a*) Induction coil.

(*b*) Attracted armature type buzzer.

(*c*) Revolving commutator.

(*d*) Timed spark.

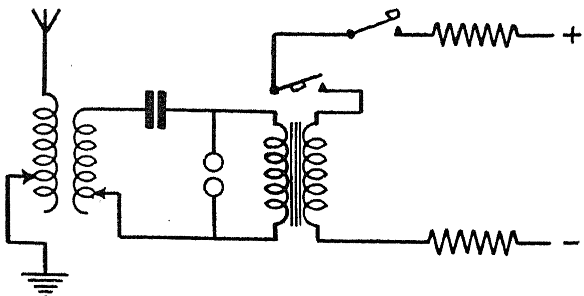


Fig. 54.

40. Induction Coil Method.—One of the earliest methods of producing high frequency oscillatory currents for use in wireless telegraphy utilised an induction coil (see Fig. 54). This method is only suitable for very low powers, but is still used where only a short range is required on account of its simplicity. The fact that a direct current supply from several accumulators is the only source of power required enables this method to be used when alternating current is not available.

41. Attracted Armature Type Buzzer.—A method suitable for very short ranges only, but used extensively for exciting an oscillatory circuit for testing receiving apparatus and for tuning purposes, consists of a D.C. supply made and broken by a buzzer of the attracted armature type (see Fig. 55).

The condenser C is alternately charged and discharged by the vibrating contact and sets up oscillations in the circuit composed of the condenser C, the inductance L, and the spark which occurs at the contacts X and Y.

When contact is made at X and Y current flows through the coils of the electromagnet, the armature is attracted, and the contact at XY broken. The energy stored in the highly inductive coils of the electromagnet charges up the condenser, which discharges as soon as Y returns sufficiently close to X to enable a spark to pass.

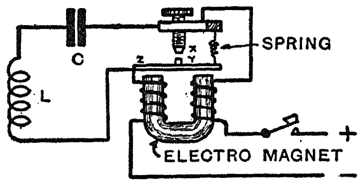


Fig. 55.

42. Revolving Commutator.—Instead of the buzzer used in the method described in the preceding paragraph, a revolving commutator can be used as shown in Fig. 56.

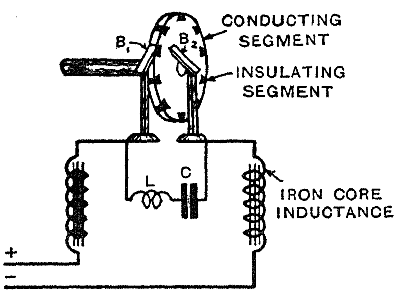


Fig. 56.

The action in this case is similar to that in the previous case, sparking at the brushes occurring as soon as the brush B_1 is near enough to a conducting segment, thus discharging the condenser which had been charged up when the brush was on the preceding conducting segment. Excessive sparking occurs if too much power is used.

In this method, and also in the buzzer method, the spark is of such short duration that very little of the oscillatory energy transferred from the closed circuit to the aerial circuit is returned to the closed circuit. These methods, therefore, have a "quenching effect" (see page 79).

43. Timed Spark System.—The revolving commutator method described in the preceding section cannot be used for high voltages and high power on account of excessive sparking.

A similar method, using a revolving spark gap instead of the commutator has been developed by the Marconi Company, and used with a high voltage direct current supply. This method gives waves which are only slightly damped.

A disc carrying spark contacts in place of the conducting segments of the commutator revolves between two fixed contacts, and two sparks in series occur when the gaps between the contacts are sufficiently small. With one disc, as in ordinary spark systems described later, the oscillations in the aerial, and therefore the wave train transmitted, which are produced by one spark are rapidly damped out in a short time of the order of $\frac{1}{10000}$ of a second. The time between two sparks is of the order of $\frac{1}{500}$ of a second. Consequently a comparatively large interval of time occurs between successive wave trains during which no energy is transmitted.

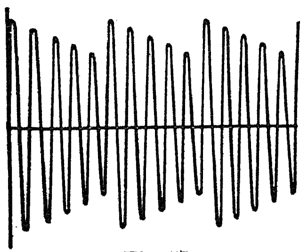


Fig. 57.

In the timed spark system developed by the Marconi Company and used at several large stations, a second spark disc is used which produces oscillations in the aerial during the period between the successive series of oscillations produced by the first gap. The oscillations produced by the two sets of spark gaps overlap, and the timing of the sparks is so adjusted that the two sets of oscillations are in phase. The result is the production of continuous oscillations which vary slightly in amplitude as shown in Fig. 57.

Good results have been obtained from this system, but difficulty is experienced in getting the two sets of oscillations in phase. The methods of producing pure continuous, undamped waves are more satisfactory, and it is unlikely that the timed spark system will be adopted in future installations.

The station at Carnarvon uses two 5,000 volt D.C. generators in series, giving 500 kW at 10,000 volts.

44. Spark Gap Methods using Alternating Current.—With the exception of a few stations using the timed spark system, practically all wireless transmitting sets used for producing damped waves use alternating current, except in the case of sets of less than $\frac{1}{2}$ kW.

In some cases rotary converters are used, but motor alternators are more often used on account of the ease with which the voltage can be varied.

45. Alternator-Transformer Method.—The usual method of supplying power for energising an oscillatory circuit by means of a spark gap is by means of an alternator and a step-up transformer, as shown in Fig. 58.

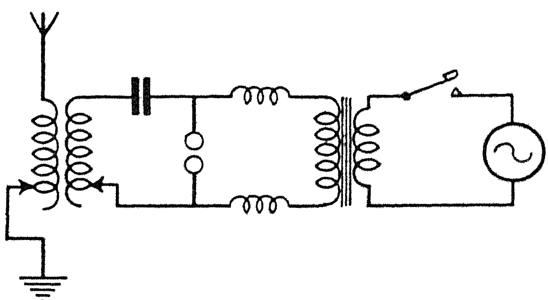


Fig. 58.

As shown in Chapter III., the note heard in the telephones by the operator at the receiving station has a frequency equal to that at which the spark passes. If a spark passes every half cycle of the alternating current supply, the frequency of the alternator is half that of the note in the telephones. A note frequency of 500 to 1,000 is found to be most suitable for reception so that the note can be distinguished from atmospheric disturbances. This means that the alternator frequency is 250 to 500.

If a low spark frequency is required the alternator circuit can be tuned to the alternator frequency, and the spark gap lengthened so that a spark occurs every few cycles. This

was used at the Eiffel Tower, at one time, for sending time signals.

As a rule the spark gap is arranged to break down every half cycle, although in the early days of wireless telegraphy low frequency alternators, as used for lighting and power, were used, and the spark gap arranged to break down long before the maximum voltage was reached, so that several sparks occurred at irregular intervals each half cycle. This produced a very poor note at the receiving station, and the method was soon superseded.

Choke coils are placed in series with the transformer, either in the primary or secondary circuit to prevent a continuous arc forming. They cause the P.D. across the spark gap to fall when a spark passes. If the inductance of the alternator is large enough these choke coils can be omitted, but for sets of all but very small powers they are usually employed and connected in the secondary circuit to prevent any oscillations from flowing back through the transformer and subjecting the end turns to heavy potential stresses.

46. Prevention of Arcing.—The prevention of arcing is more difficult with high power sets than with sets of low power, and special methods have to be adopted in the former case. The following are methods used for this purpose:—

(*a*) Fixed spark gap with air blast.

(*b*) Asynchronous rotary spark gap, with or without air blast.

(*c*) Synchronous rotary spark gap, with or without air blast.

(*d*) Quenched gap.

The latter method not only prevents the formation of an arc, but in addition it reduces the time during which the spark passes to such a small period that there is no time for the energy transferred to the aerial circuit to be transferred back to the spark gap circuit. This prevents dissipation of oscillatory energy in the spark gap and allows more of the oscillatory energy to be radiated from the aerial (see page 78).

47. Asynchronous Rotary Spark Gap.—Instead of being composed of two fixed electrodes, the spark gap very often consists of a number of electrodes on a wheel revolving between two fixed electrodes. Whenever the revolving electrodes are sufficiently near the fixed electrodes a spark will pass between the two fixed electrodes by way of the two revolving electrodes near them. The spark frequency can thus be made independent of the alternator frequency, and arcing is prevented by the revolving electrodes.

This method gives a very poor note, as the sparking is not very regular owing to the electrodes being in position for sparking very often when the condenser is not sufficiently charged to break down the gap. This disadvantage is overcome in the synchronous rotary spark gap.

48. Synchronous Rotary Spark Gap.—In most spark gap transmitters of anything but very low powers, the rotary gap is mounted on the shaft of the alternator. The number of moving electrodes is made equal to the number of poles, and one spark per half cycle is therefore obtained.

The positions of the stationary electrodes can be adjusted so that the spark occurs when the P.D. across the condenser is a maximum and the transformer current zero. Regular sparking occurs, arcing is prevented, and a musical note is obtained.

Usually the alternator circuit is tuned to the alternator frequency so that the condenser P.D. can be made as large as possible, and the power supplied by the alternator at a high power factor. Air blasts are used to cool the electrodes of the larger sets. The Marconi Company have used this system to a great extent for sets ranging from $\frac{1}{2}$ kW up to about 100 kW

Fig. 59 shows a typical spark set of this nature. The receiving apparatus is connected across a very short spark gap, called an **earth arrester**, which is connected in the earth lead. This earth arrester allows the transmitting current to spark across it, and also protects the receiving gear against heavy atmospheric discharges, but the small received current cannot pass across the gap, and is compelled to flow through the detector.

Robust detectors must be used with this arrangement as fairly large potentials are applied to them when transmission

occurs, but this can be prevented by using a switch to cut out the detector when transmitting. This switch may be hand-operated or electromagnetically operated by the transmitting key.

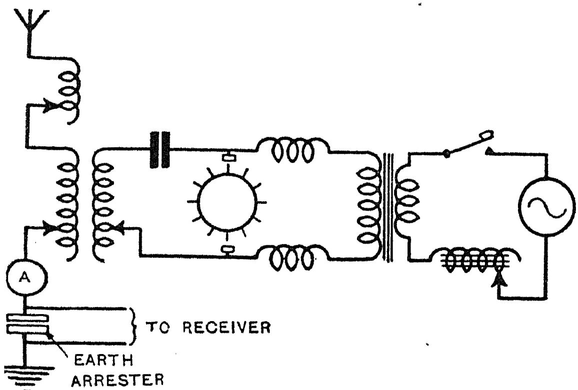


Fig. 59.

49. Quenched Gap.—As shown in Chapter I., the energy transferred to the aerial circuit from an oscillatory circuit containing a spark gap is transferred backwards and forwards between the two circuits, so long as the spark gap remains conductive. This causes the radiation of two waves of different frequencies.

If the coupling between the two circuits is made sufficiently weak, the transference of energy takes place slowly, only one beat occurs, and a good proportion of the energy transferred to the aerial circuit is dissipated in the aerial circuit only. On the other hand, however, energy is being dissipated in the spark gap so long as an oscillatory current is present in the spark gap circuit, and the total efficiency is only low. Accordingly, therefore, a compromise has to be effected, and the coupling coefficient is usually made about 5 per cent. With this coupling the decrement of the aerial circuit is usually sufficient to prevent two peaks from showing in the resonance curve, and a wave of one frequency only is radiated.

If the spark gap can be arranged to "quench" or become non-conducting at the instant the oscillatory energy is all transferred to the aerial circuit for the first time, the energy is all dissipated in the aerial circuit instead of partly in the

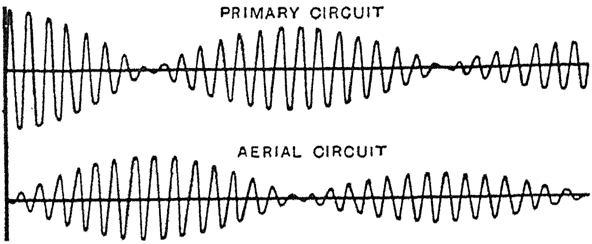


Fig. 60.

spark gap, and tight coupling can be used. Fig. 60 shows the nature of the oscillations with an ordinary spark gap with tight coupling between the two oscillatory circuits, and Fig. 61 shows the nature of the oscillations when the spark is quenched after $2\frac{1}{2}$ oscillations.

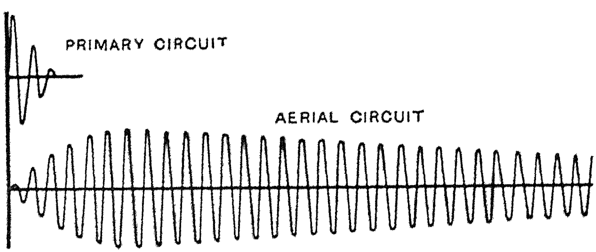


Fig. 61.

Max Wien and Lepel investigated and introduced originally what is now known as the **quenched gap.** The quenching properties of the gap are due to its extreme shortness and the large amount of metal composing the electrodes, which rapidly conduct the heat away. The Telefunken Company have developed the quenched gap, and have used it extensively.

A typical quenched spark gap is shown in Fig. 62. The electrodes consist usually of copper discs whose faces are covered with silver plates. Mica rings are placed between the electrodes at the outer edges, and circular grooves are cut in the faces of the electrodes to prevent sparking at the mica rings, whilst circular flanges are fitted to facilitate cooling. The rapid cooling of the gap de-ionises the gas, and thus quenches the spark.

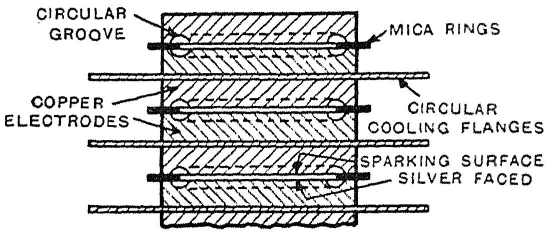


Fig. 62.

A number of gaps are usually employed in series, each gap being about 0·2 mm. long. The number of single gaps used can be varied by short-circuiting any of the gaps by means of clips, according to the power it is desired to use. Approximately 1,000 volts per gap are used, usually about 1,200. A typical $1\frac{1}{2}$ kW set uses eight gaps at a voltage of 8,000, and a typical 40 kW set uses 50 gaps at a voltage of 60,000.

The Telefunken Company use an alternator frequency of 500 and spark every half cycle, thus giving a note whose frequency is 1,000, compared with 500 to 600 generally used in other spark sets. A note whose frequency is 1,000 is very distinctive and easily distinguished from atmospheric disturbances, but is apt to be fatiguing to an operator.

An idea of the time available for quenching can be obtained by taking a typical case. Assuming the wave-length to be 600 metres, the frequency will be 500,000 cycles per second, therefore $2\frac{1}{2}$ cycles take $\frac{1}{200000}$ sec., *i.e.* if quenching takes place at the end of $2\frac{1}{2}$ oscillations, as shown in Fig. 61, the time during which the spark passes is $\frac{1}{200000}$ second. If the spark frequency is 1,000, a spark occurs every $\frac{1}{1000}$ of a second.

This method of inducing oscillations in the aerial is sometimes referred to as **shock-excitation** or **impact-excitation.** The use of tight coupling (20 to 30 per cent.) causes rapid transference of energy to the aerial circuit with consequent high initial amplitude of the aerial oscillations. This tends to set up oscillations in any neighbouring aerials, even if they are not tuned to the same wave-length, by inducing forced oscillations.

50. Methods of Producing Undamped Oscillatory Currents.—Wireless telegraphy and telephony sets producing damped waves are gradually being replaced by sets which produce continuous or undamped waves. Several methods of producing undamped oscillations are in use, each of which has its supporters, and installations of each kind are still being fitted. The following are the various methods :—

(*a*) Arc.
(*b*) High frequency alternator.
(*c*) Frequency changing transformer or valve.
(*d*) Thermionic valve.

Method (*c*) has not been adopted very largely, but opinion is divided as to the relative superiority of the other methods. Several other methods have been suggested but have not been applied commercially.

51. The Arc System.—In 1900 Duddell discovered that when an inductance and a condenser were connected in series across an ordinary direct current arc (Fig. 63) a steady oscillation was set up in the circuit when the inductance and capacity had a certain ratio. Under these conditions the arc gave out a musical note, hence the oscillations set up were of audible frequency. The approximate formula for the frequency is the usual $f = \frac{1}{2\pi\sqrt{LC}}$, but in this case the frequency also depends

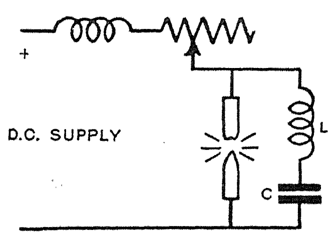


Fig. 63.

slightly on the length of the arc and on the current through it. Duddell's arrangement was not suitable for producing oscillations of the high frequencies necessary for wireless telegraphy, and Poulsen was responsible for the improvements necessary to make the Duddell arc suitable for high frequencies.

Poulsen (in 1903) found that the following modifications were necessary to keep the arc stable:—

(*a*) The use of a copper positive electrode, water-cooled, and a slowly rotating carbon negative electrode.

(*b*) A hydrogenous atmosphere in which the arc is maintained.

(*c*) A transverse magnetic field across the arc.

The action of these modifications can be seen by further consideration of the arc beyond that given in Chapter I., where it is shown that the shape of the characteristic curve is responsible for the arc being suitable for producing undamped oscillations.

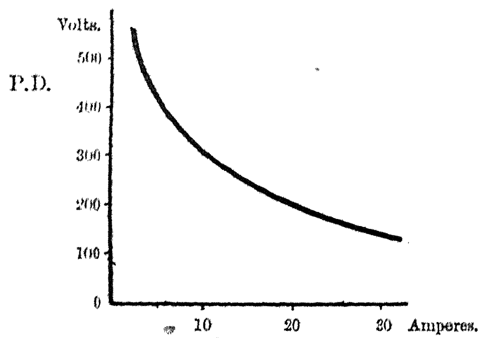


Fig. 64.

A typical characteristic curve of an arc is shown in Fig. 64. It will be seen that, contrary to Ohm's Law, the resistance of the arc decreases as the current increases. When an electric field is applied to an air gap the few free ions usually present have their velocities increased. Conse-

quently the collision of these ions with molecules of gas causes further ionisation until finally the gap breaks down and becomes a conductor if the applied E.M.F. is large enough.

When the gap becomes a conductor the positive ions move towards the negative electrode and the negative ions move towards the positive electrode. Some of them re-unite but the majority reach the electrodes and give up their charges, thus constituting the current of electricity across the gap. Once the current has started the temperature of the electrodes rises and causes increased ionisation, and if the P.D. remains sufficiently high an arc is formed and not merely a spark.

If the current is increased the ionisation increases and the arc becomes a better conductor. A certain number of ions accumulate at the electrodes, as the electrodes do not absorb the charges immediately, and they consequently exert a back E.M.F. If the current is increased the number of accumulated ions increases and consequently the back E.M.F. is increased, causing a drop in the P.D.

It will be seen, therefore, that for the arc to remain stable, and to respond readily to high frequency oscillations, it is necessary for the number of accumulated ions to alter readily at a high frequency in response to the high frequency oscillations. Hence it is necessary to remove the heat as quickly as possible. This is done by water-cooling the anode and sides of the arc chamber, maintaining the arc in an atmosphere of hydrogen or hydro-carbons to increase the convectivity, and increasing the length of the arc by a magnetic field. Hydrogen molecules have very small mass, and therefore move readily between the electrodes and so follow the change in current more quickly than in the case of air, and give a steeper characteristic.

The characteristic shown in Fig. 64 is called the **static characteristic** as it is only correct when the conditions are varied gradually. When the current is altering rapidly the conditions are represented by the **kinetic characteristic** of the nature shown in Fig. 65. After a large current has been flowing the temperature remains higher and the gas remains ionised, and the P.D. is consequently lower than that given by the static characteristic for the value of the lower current.

The kinetic P.D. will thus be lower than the static P.D. when the current is decreasing, and higher when the current is increasing.

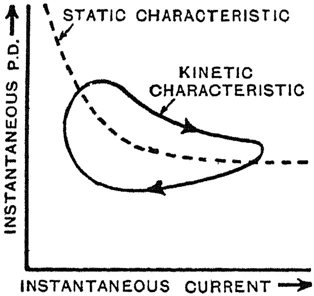


Fig. 65.

The oscillatory current is superimposed on the steady current through the arc from the D.C. supply, and if the amplitude of the oscillatory current is less than the value of the steady current the instantaneous value of the current through the arc is given by Fig. 66. An oscillation of this kind is called an "oscillation of the first type."

If the amplitude of the oscillation is greater than the value of the steady current the arc is extinguished as shown in Fig. 67. The condenser is then charged up by the steady current until its P.D. is sufficient to start up the arc again. Such an oscillation is called an "oscillation of the second type."

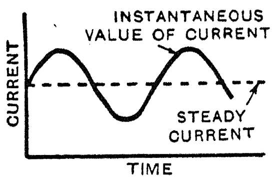


Fig. 66.

Oscillations of this kind are the ones used in the Poulsen arc, whereas oscillations of the first type were obtained in the Duddell arc. The time taken in charging up the condenser to the necessary P.D. determines the time when the arc re-ignites.

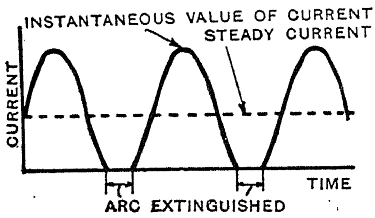


Fig. 67.

The frequency of the oscillations is therefore not absolutely dependent on the values of L and C. The complete theory of the Poulsen arc is, however, still not entirely elucidated, and recent researches by Pedersen appear to show that the generally accepted theory is not upheld by the behaviour of

a Poulsen arc where the arc is short. (See P. O. Pedersen "On the Poulsen Arc and its Theory," *Pro. Inst. Radio Engineers*, Vol. V., No. 4, and Vol. VII., No. 3.)

Figs. 68 and 69 show two typical Poulsen arcs manufactured by C. F. Elwell. The field coils of the two electromagnets are connected in series with the D.C. supply to the arc electrodes, and therefore act as the choke coils required for satisfactory working (see page 15). The carbon electrode is rotated slowly by a small motor to prevent uneven burning. The hydrogenous atmosphere is obtained by allowing alcohol or methylated spirits to drip into the arc chamber, where it is vaporised.

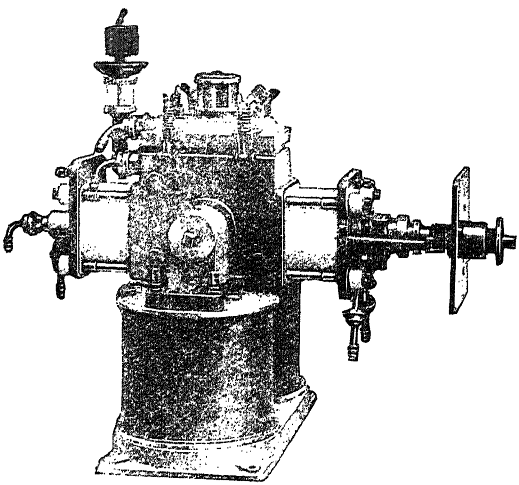


Fig. 68.

For signalling purposes the arc is usually connected directly in the aerial circuit as shown in Fig. 70, a condenser of large capacity being connected between the arc and earth to insulate the D.C. supply.

Signalling cannot be carried out by making and breaking the supply to the arc, as in the case of the spark gap, or the

arc would go out, and have to be re-struck like an ordinary arc lamp. One method used is the "marking and spacing method" in which the wave-length is altered by the signalling

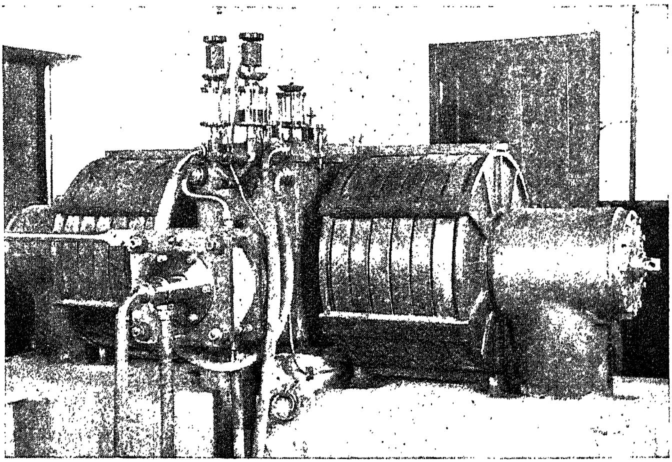


Fig. 69.

key short-circuiting a portion of the inductance. Two waves are therefore transmitted, the **marking wave** when the key is pressed and the **spacing wave** between signals. The latter may cause interference with other stations, and may be confused with the marking wave at the receiving station. Another method, which involves more apparatus, but does not cause two waves to be radiated, is the **back shunt method.** In this case signalling is effected by changing over the arc to a **back shunt** or dummy aerial which does not radiate. A change-over key is required which puts both circuits in parallel before breaking the aerial circuit, otherwise the arc would be put out.

The arc may be used with a coupled circuit, as in the case of a spark gap, but this is not usual as the arc is very selective and of low resistance when connected straight in the

aerial. Recently, however, a coupled circuit has been adopted at the Leafield station and has been found to eliminate to a large extent various harmonics previously present in the transmitted wave.

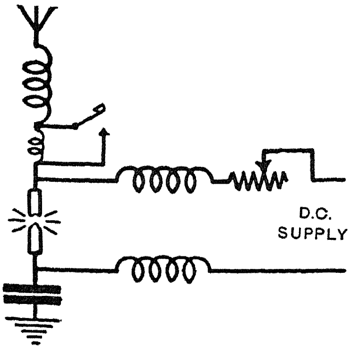


Fig. 70.

Arcs are constructed in sizes varying from 1 to 1,000 kW. Up to about 5 kW a D.C. supply at 200 to 400 volts is used, and 800 to 1200 volts is used for arcs of about 300 kW. Efficiencies of 30 to 40 per cent. (including auxiliaries but not power plant) are obtained.

52. High Frequency Alternators.—The most direct method of producing high frequency alternating currents, and the one which would naturally occur to electrical engineers, utilises an alternator.

The design of an efficient high frequency alternator for large outputs is, however, a matter of great difficulty. In order to obtain frequencies suitable for wireless telegraphy (*e.g.* 60,000 cycles per second), a large number of poles and a high speed are necessary. This means that very little space is available for the field windings, so low flux density, with consequent small output and short air gap to prevent large leakage, has to be used. The iron losses are very large at such high frequencies, and the large eddy currents oppose the flux. As a result of the difficulty in designing suitable alternators of the necessary frequency, the usual method is to build them for a lower frequency, and then to increase the frequency by special methods.

In 1890 Tesla succeeded in building a 1 kW alternator for 10,000 cycles per second, and many attempts were made to build machines of greater output at higher frequencies, but it was not until 1909 that an alternator was built capable of giving 2 kW at 100,000 cycles per second. This machine was built by Alexanderson in America, and ran at 20,000

revs. per minute. Since then machines of the Alexanderson type have been built for 200 kW at 22,000 cycles per second, the speed being 2,170 revs. per minute.

The Alexanderson alternator is of the inductor type, and Fig. 71 shows the arrangement adopted. In an inductor alternator the armature winding and the field winding are both on the stator, and the rotor carries no winding. In the Alexanderson alternator the rotor consists of a solid steel disc with radial slots cut near the periphery. The slots are filled with non-magnetic material, such as phosphor bronze, and are finished off smooth. The armature winding is enclosed in the slots between the poles on the stator, and is in two parts, one on each side of the rotor. There are twice as many slots as there are rotor teeth, consequently the number of cycles per revolution is equal to the number of poles instead of equal to the number of pairs of poles, as in the ordinary alternator.

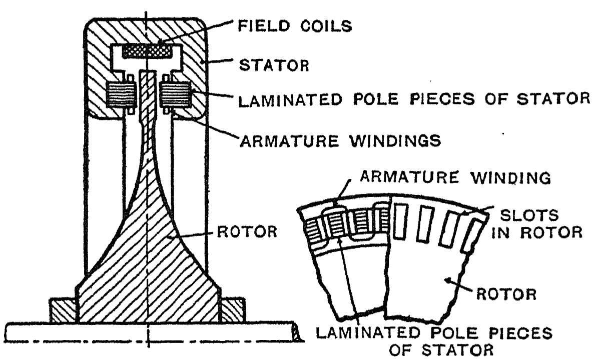


Fig. 71.

Another type of alternator which has been commercially successful is that due to Goldschmidt. The Goldschmidt alternator is based on the production of an alternating current in the stator of a single phase alternator by the armature reaction of the rotor, the frequency of this current being twice that of the current in the rotor.

Most students of electrical engineering are familiar with

the production of a double frequency current in the field coils of a single phase alternator, but for the benefit of those who are not the following explanation is given.

The alternating current induced in the rotor of a single phase alternator, which is excited by direct current passing through the field winding on the stator, produces an alternating flux which is stationary relative to the rotor. This flux is equivalent to the resultant of two fluxes rotating in opposite directions at a speed equal to that of the rotor relative to the rotor. Consequently one of these fluxes is moving through space at twice the rotor speed, and the other flux is stationary in space. The former produces an alternating current in the stator of a frequency twice that of the current in the rotor.

The alternating current produced in the stator produces a pulsating field, which can be resolved into two fields rotating in opposite directions at speeds equal to twice that of the rotor. The one whose direction is opposite to that of the rotor therefore induces a current in the rotor of a frequency equal to three times that of the rotor main current. These reactions can be repeated indefinitely in theory, but in practice the losses become very large.

It should be noted that the speeds referred to are "electrical speeds," and are only equal to "mechanical speeds" in the case of a two-pole machine.

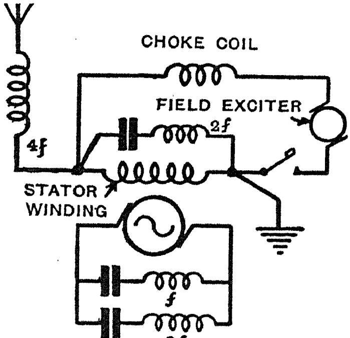


Fig. 72.

In an ordinary single phase machine the multiple frequency currents are only of comparatively small magnitude, but in the Goldschmidt alternator the whole object is to make these currents as large as possible. This is achieved by tuning various circuits connected to the stator and rotor. An inductance and a capacity are connected across the stator winding and tuned to twice the frequency of the rotor. The rotor is con-

nected to a circuit tuned to three times the frequency of the rotor main current, and the aerial circuit, tuned to four times the fundamental frequency, is usually connected to the stator (see Fig. 72).

Signalling is usually effected by controlling the exciting current, and special means have to be adopted to keep the speed constant.

The principle used in the Goldschmidt alternator has also been utilised by various people, who used several alternators coupled together. In some cases the rotor of one machine was used to excite the stator of the next machine, thus giving a double frequency current in the rotor of the second machine, and this was used to excite the stator of the next machine, and so on. In other cases two-phase current was used to give a rotating field.

Two 150 kW Goldschmidt high frequency alternators have been in use at Eilvese in Germany for some time. They are driven by direct current motors at 3,150 r.p.m., and the fundamental frequency is doubled to give a frequency of 20,800 by tapping off the stator, and three times the fundamental frequency can be obtained by tapping the rotor, giving a frequency of 30,800, which corresponds to a wave-length of 9,700 metres. Special speed regulators are fitted to keep the number of revolutions constant within 0·02 per cent. by altering the resistance in the exciter circuit.

Overall efficiencies of 35 to 50 per cent. are obtained with high frequency alternators, but the capital cost and maintenance are higher than those of the arc.

53. Frequency Changing Transformers.—On account of the difficulties experienced in designing high frequency alternators, various methods of multiplying the frequency by means of transformers have been tried. These methods depend for their action on the shape of the magnetisation curve for iron. Direct current is used to magnetise the iron to the condition corresponding to the point P at the end of the straight part of the magnetisation curve (see Fig. 73 (a)). When the field due to an alternating current is applied, the magnetisation is along the straight part of the curve during one half cycle, and is along the saturation part during the other half cycle. The E.M.F. induced during one half cycle

is, therefore, greater than that induced during the other half cycle, and is of the nature shown in Fig. 73 (*b*).

If two transformers of this nature are used they can be arranged to work 180° out of phase, as shown in Fig. 73 (*b*), thus giving a resultant of the nature shown in Fig. 73 (*c*). It will be seen that the frequency of this E.M.F. is twice that of the A.C. supply. Actually, the curves of E.M.F. produced are distorted, due to hysteresis, and are not quite as shown in Figs. 73 (*b*) and 73 (*c*).

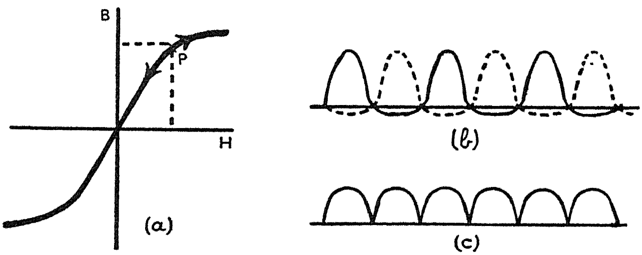


Fig. 73.

Frequency changing transformers have been tried successfully, especially by the Telefunken Company, who have installed alternators giving a frequency of about 10,000 cycles per second, and have multiplied this frequency to 40,000 cycles per second by means of transformers.

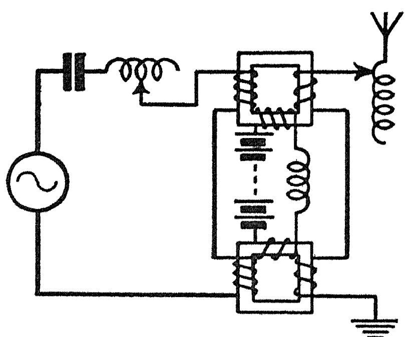


Fig. 74.

In the Joly type of frequency changing transformer two iron cores are used, and both are magnetised to the knee of the magnetisation curve by separate windings on each, connected in series, carrying direct current. The primary windings on the two cores are connected in series with the A.C.

supply, and the circuit is tuned to the alternator frequency (see Fig. 74). The secondary windings are connected in series with the aerial (or in series with the primary windings of the next Joly transformer, if more than one are used), and the directions of the various windings are arranged so that the E.M.F.'s induced in the aerial by both transformers are 180° out of phase. A choke coil is put in series with the D.C. supply to stop the passage of any alternating current.

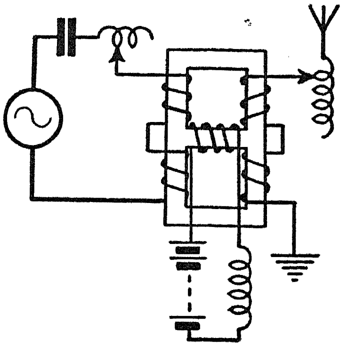


Fig. 75.

Vallauri used a similar arrangement to Joly, but made the portion of each core carrying the D.C. winding into one, as shown in Fig. 75.

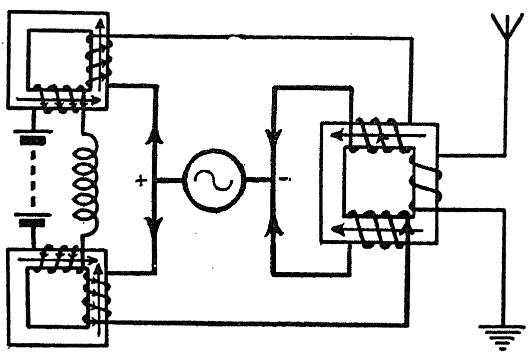


Fig. 76.

Three iron cores were used by Plohl, whose arrangement is shown in Fig. 76. In this case the current through the saturated core is greater than that through the unsaturated core, in order to produce the required back E.M.F. The

resultant flux passing through the secondary of the third transformer is, therefore, in the same direction each half cycle, thus producing an E.M.F. in the aerial of twice the alternator frequency.

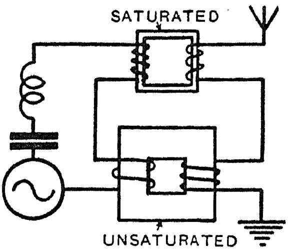


Fig. 77.

Clinker uses one core that is saturated and the other unsaturated, as shown in Fig. 77. The resultant E.M.F. has a very pronounced third harmonic, due to one of the flux curves being flat topped and the other peaked, and this third harmonic is used as the current of three times the alternator frequency.

Taylor transforms three phase current to single phase by a similar method. Three primary windings from the three phases are connected in series with three separate choking coils with saturated cores (Fig. 78). The core of the transformer is unsaturated. The current curve for each phase is peaked, and contains a pronounced third harmonic. Since the three currents are 120 degrees out of phase, the third harmonics are in phase in their effect on the magnetic core, whereas the fundamental components neutralise each other.

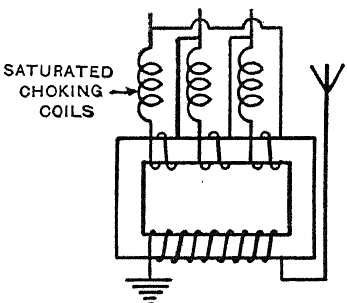


Fig. 78.

A frequency-multiplying device which uses a transformer whose core is built up of very fine iron wires (0·05 mm. in diameter) has been used in Germany to produce as high a harmonic as the forty-seventh with 50 per cent. efficiency. An aerial output of 1·5 kW and waves as short as 750 metres have been obtained easily by this means from a 3·5 kW, 7,600 cycle generator. An extremely sensitive speed regulator, based on the Tirril principle, is used to keep the speed of the driving motor within 0·0001 per cent. between no load and full load.

54. Valves used as Frequency Changers.—Another method used for changing frequency employs rectifying valves. This method has not been employed very much for high frequency changing, but is used very largely for interrupted continuous wave work to produce a note of twice the alternator frequency.

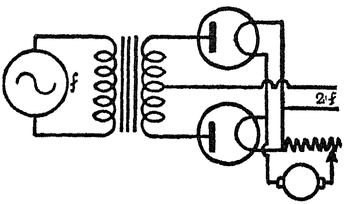


Fig. 79.

Two rectifying valves are connected to the source of alternating current through a transformer, as shown in Fig. 79.

During one half cycle current flows through one valve only, and during the reverse half cycle current flows through the other valve only. Rectified current of twice the alternator frequency is, therefore, produced, and can be utilised to produce oscillations in a tuned circuit.

By connecting a suitable condenser across the output leads the variations in amplitude of the rectified current can be smoothed out and a direct current source obtained.

55. Thermionic Valve.—Within recent years great progress has been made in methods of producing undamped high frequency oscillatory currents by means of thermionic valves. These methods are described more fully in Chapter VII., and the main principle only of these methods is given here.

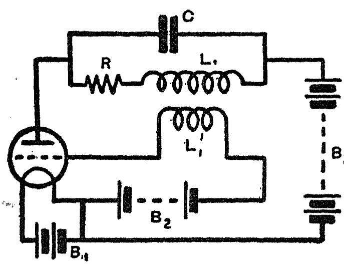


Fig. 80.

Consider a thermionic valve connected as shown in Fig. 80. The battery B_1 is used to make incandescent the filament of the valve. B_2 is used to give the required potential to the grid, and B_3 is a battery of fairly high voltage supplying current through the valve *via* the inductance L and resistance R.

As stated in Chapter III., current will only pass through the valve in one direction, viz. from anode to filament, and the incandescent filament facilitates this. The amount of current flowing is controlled by the potential of the grid.

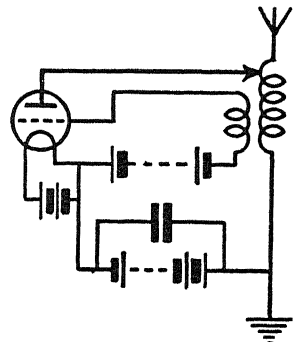


Fig. 81.

Now suppose an oscillatory current set up by some means in the circuit CLR. This will induce an E.M.F. in the inductance L′ coupled to L, which causes an oscillatory current to flow round the grid circuit through the valve, thus varying the potential of the grid with respect to the filament. As a result, the anode current varies correspondingly, and an oscillatory current, whose frequency is equal to that of the oscillatory current in the circuit CLR, is super-imposed on the steady anode current. This oscillatory current induces an E.M.F. in L′ which again varies the grid potential, and if the conditions are such that the various currents have the correct phase, the oscillations are maintained, and undamped oscillations are set up in the circuit CLR, the losses being supplied by the anode battery B_3. A condenser is usually connected across this battery to carry the high frequency component of the anode current. Any disturbance in the circuit, such as switching on the battery supplies, is usually sufficient to start the oscillations.

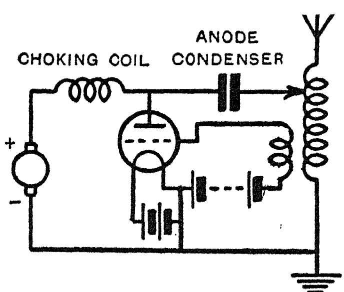


Fig. 82.

The aerial circuit can be coupled to the oscillatory circuit, or may replace the circuit, as shown in Fig. 81. In this case the filament of the valve is at a potential above earth equal

to the anode battery voltage, which may be very high in large sets where high tension machines are used instead of a battery. To avoid this the circuit shown in Fig. 82 is largely used. In this case the oscillatory component of the anode current passes through the anode condenser, and is prevented from passing through the anode supply by the choking coil.

Signalling can be effected by making and breaking the anode supply circuit.

CHAPTER V.

THERMIONIC VALVES—THEORY AND CONSTRUCTION.

56. Introductory.—In 1904 J. A. Fleming used the two electrode valve, or diode, for rectifying high frequency oscillatory currents used in wireless telegraphy. In 1907 Lee de Forest introduced a third electrode into Fleming's two electrode valve, and thus produced the three electrode valve or triode whose development has acted as an enormous stimulus to the progress of wireless telegraphy and telephony apart from its many other applications.

The term valve, in spite of many attempts to abolish its use, appears to have come to stay, and is almost universally used in everyday life by both wireless engineers and the ever growing number of wireless amateurs. Such terms as thermionic tubes, triodes and diodes, although perhaps preferable from a scientific point of view, have not been adopted to a very great extent except in technical literature.

In view of the general use of the term valve, and the likelihood of its still wider use owing to the increasing popularity of "broadcast wireless telephony," this term has been used throughout this book.

The requirements of wireless telegraphy during the war caused rapid developments in the construction and application of the valve, and since the war these developments have continued, and the lessons learnt during the war are being gradually embodied. Transmitting valves of larger and still larger outputs are being attempted, and great endeavours are being made to reduce the power consumption of receiving valves without impairing their efficiency.

57. The Electron Theory.—As the reader is no doubt aware, the generally accepted theory of the construction of matter is that an atom of any substance is composed of a nucleus of positive electricity surrounded by a number of negative atoms of electricity called **electrons.** The number and arrangement of electrons present in an atom of matter determines its properties, and the removal of electrons may simply cause the atom to become positively charged, or may even change the properties of the substance completely and produce what is known to us as quite a different substance. The addition of electrons may similarly give the substance a negative charge or change its properties altogether.

Electrons are of very small mass and are in constant motion with a high velocity, Their mass and charge have been measured and are constant for all substances. The mass of an electron is 9×10^{-28} grams and is equal to $\frac{1}{1850}$ of that of a hydrogen atom. The charge on an electron is $1 \cdot 6 \times 10^{-20}$ electromagnetic units or $1 \cdot 6 \times 10^{-19}$ coulombs.

A current of electricity may consist of a flow of electrons unaccompanied by any atoms or molecules of matter, or it may consist of a flow of atoms or molecules having either a surplus of electrons or a deficit. Atoms or molecules with a surplus of electrons are negatively charged and are called **negative ions**; if positively charged, *i.e.* with a deficit of electrons, they are called **positive ions.**

Conductors of electricity consist of atoms in which some of the electrons are constantly moving backwards and forwards between adjacent atoms. When a difference of potential is applied between any two parts of the conductor the free electrons move in one direction under the influence of the electric field and so produce an electric current. Where ionisation takes place in electrolytes and gases electric currents are produced by the passage of ions under the influence of an electric field. When a current flows through a dielectric it is only of short duration in one direction and is produced by a slight displacement of the electrons inside the atom, which is then under strain. If the electric field producing the strain is released, the electrons return to their normal arrangement and in so doing produce a current in the reverse direction.

58. Emission of Electrons from Hot Bodies.—Under normal conditions the rapidly moving electrons in the atoms of a substance which is a conductor of electricity seldom escape from the surface of the substance. If, however, the substance is heated, the velocity of the electrons is increased, and, in the case of some of the electrons, is sufficient to overcome the attraction of the positive nucleus; hence some electrons are carried outside the surface of the substance. If there is no electric field applied in the space surrounding the heated substance, these electrons fall back into the substance and may be expelled again in their turn. If an external electric field is applied the escaped electrons are acted upon and move away from the hot body, which continues to emit electrons.

The higher the temperature of the hot body the greater is the number of electrons emitted; and the formula for the number of electrons emitted when the hot body is in a vacuum is

$$N = A\sqrt{T}e^{-\frac{b}{T}}$$

where $N =$ the number of electrons emitted per sq. cm. per second, $T =$ the absolute temperature of the body, $e =$ the base of Napierian logarithms, $A =$ a constant depending on the substance, and $b =$ a constant depending on the substance but approximately 5×10^4 for all substances.

It will be seen that as this formula represents an exponential curve, the emission of electrons increases very rapidly as the temperature rises. It is an advantage, therefore, to use as high a temperature as possible, if good emission is required, and substances with high melting points are used.

The substances found to be the most suitable emitters of electrons are platinum, tungsten, and tantalum. These are often coated with substances such as lime or barium oxide when used in thermionic valves (see page 110). They are used to form the filament of a valve and are heated to incandescence by an electric current.

In the case of the filament of a valve variations in potential and temperature occur along the filament, consequently the emission is not uniform. This problem has been attacked

by Stead* and other investigators whose papers should be consulted if further information is required.

59. Effect of the Presence of Gas.—When a gas is ionised it becomes a conductor of electricity due to the motion of the ions under the influence of an electric field.

In an exhausted two electrode thermionic valve, the current between the anode and filament is caused simply by the flow of electrons from the heated filament under the influence of the electric field due to the difference in potential of the two electrodes. The passage of these negative charges of electricity from filament to anode is equivalent to a current of electricity flowing from the anode to filament (Fig. 83). If the P.D. between the anode and filament is reversed no current will flow as no electrons are emitted from the filament.

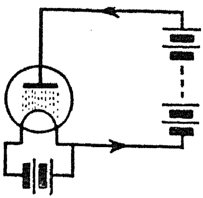


Fig. 83.

If gas is present in the valve the impact of the electrons emitted from the filament may be sufficient to ionise the gas, in which case the current which flows is produced by the flow of both ions and free electrons. If the ionisation is sufficiently great a blue glow is visible.

Completely exhausted valves are referred to as **hard** valves, while those in which a trace of gas or air is left are termed **soft** valves. The latter were used originally before exhausting processes were sufficiently developed to give the "hardness" used to-day. They gave excellent results, but owing to the anode current depending largely on the pressure of the gas, which was affected by temperature and occlusion, they required careful adjustment. In addition the life of the filament was short owing to the continuous bombardment by the positive ions.

60. The Space Charge.—Unless the P.D. between the anode and filament is sufficiently great to remove the electrons as fast as they are emitted, a cloud of electrons called the **space charge** accumulates round the filament. These electrons reduce the anode current by repelling electrons

* See *J.I.E.E.*, Vol. 59, p. 427, April 1921.

which would otherwise have had sufficient velocity to escape from the filament, and by causing electrons to return to the filament instead of being attracted to the anode.

Instead of increasing the anode voltage to remove the space charge, a positively charged body can be introduced between the anode and filament to neutralise the charge. If gas is present the positive ions on their way to the filament also tend to neutralise the space charge.

If the anode voltage is sufficiently great to cause all the electrons emitted by the filament to be removed as fast as they are emitted, and to reach the anode, the anode current is then a maximum and is called the **saturation current.** The value of this current cannot be increased by increasing the anode voltage, but can only be increased by raising the temperature of the filament and so increasing the emission of electrons.

The space charge is responsible for the curved shape of the characteristic curve showing the relation between anode voltage and current, which enables the thermionic valve to be used as a detector of wireless signals.

61. Introduction of the Third Electrode.—If a third electrode be introduced between the anode and filament, its potential relative to the filament is bound to have an effect on the flow of electrons from the filament to the anode. Fig. 84 shows an arrangement for varying the potential of the third electrode, usually called the grid, with respect to the filament. By means of the potentiometer the grid can be made either positive or negative with respect to the filament.

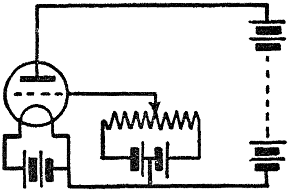


Fig. 84.

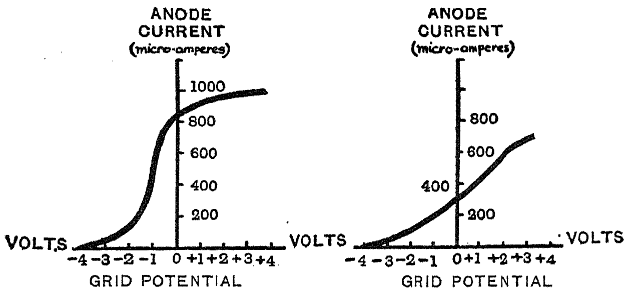
By making the grid sufficiently negative all the electrons emitted by the filament are either repelled back into the filament, or if their velocity is sufficiently great for them to reach the grid they are absorbed by it and flow back to the filament *via* the potentiometer. Under these circumstances no electrons reach the anode and there is therefore no anode current.

When the grid is made less negative its repelling force on

the electrons emitted from the filament is decreased, and, as a result, more electrons reach it and are absorbed by it, some even shoot past it or through it if it consists of a spiral or fine mesh. Consequently both the grid current and the anode current are increased.

The effect of making the grid positive is to neutralise the space charge, thus tending to increase the anode current. In addition, the grid current is increased by the attraction of electrons to the grid, thus tending to decrease the anode current.

Typical characteristic curves, showing the relation between anode current and grid potential for both hard and soft valves, are shown in Fig. 85. In each case the anode voltage and filament current are kept constant. The steepness of the curve in the case of the soft valve compared with that in the case of the hard valve is due to the increased current produced by the flow of ions in addition to the flow of electrons.



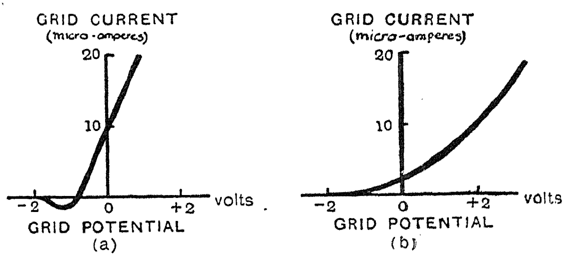
(*a*) Soft Valve. (*b*) Hard Valve.

Fig. 85.

Typical characteristic curves, showing the relation between grid current and grid potential are shown in Fig. 86. It will be seen that in the case of the soft valve the grid current becomes reversed when the grid is at a certain negative potential. This is due to the absorption of positive ions by the grid, and is known as **backlash.** As the grid is made more and more negative the movement of electrons is restricted to the immediate neighbourhood of the filament,

and consequently very little ionisation of the gas takes place, until finally no positive ions are absorbed by the grid and the grid current becomes zero.

The grid is specially constructed to have maximum effect on the anode current without producing large grid currents. The peculiar shapes of the characteristic curves enable the three electrode valve to be used for various purposes, by working tho valve under various conditions corresponding to different points on the curves. These uses are described in succeeding pages.



(*a*) Soft Valve. (*b*) Hard Valve.

Fig. 86.

62. Valve used as a Rectifier.—The two electrode valve can be used as a pure rectifier by making use of its property of allowing current to pass in one direction only, owing to the current being produced by the passage of electrons from the filament to the anode. This method is used in wireless telegraphy and telephony, and also in other cases, where it is desired to obtain a D.C. supply from an A.C. source (see page 145). In addition the curved shape of the characteristic curve for anode current and anode voltage can be utilised to give partial rectification, as shown in Chapter III.

The curvature of the characteristics showing the relation between anode current and grid potential, and between grid current and grid potential, in the three electrode valve can be similarly used to give partial rectification. These two methods are the ones practically always used for rectifying high frequency oscillatory currents in wireless telegraphy and telephony.

63. Anode Rectification.—Fig. 87 shows a circuit for anode rectification. The grid potential is adjusted by means of the potentiometer so that it falls on either of the two portions of the anode characteristic curve where the curvature changes rapidly. Under these conditions the grid current is practically zero, and the energy absorbed from the aerial circuit is negligible.

Although this method is more sensitive than that using the two electrode valve, it is seldom used, as the grid rectification method is much more sensitive.

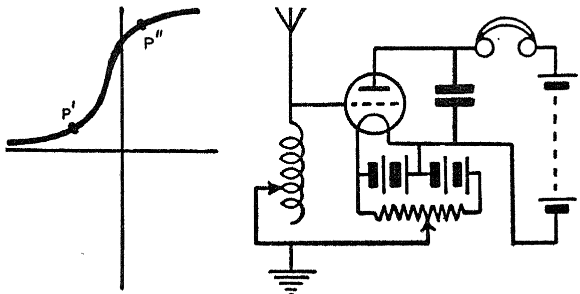


Fig. 87.

64. Grid Rectification.—The method almost always used nowadays for rectifying wireless signals is that known as **cumulative grid rectification.**

If, in the arrangement shown in Fig. 87, the potentiometer is adjusted so that the potential of the grid is such that the conditions correspond to the part of the grid current-grid potential curve where the rate of change of curvature is greatest, an alternating current in the aerial produces a rectified current between the grid and the filament, superimposed on the steady grid current.

Now consider the circuit modified by the introduction of a condenser C, and a high resistance R, as shown in Fig. 88. The high frequency rectified current which flows round the grid circuit from filament to grid, *via* the aerial inductance and the condenser C, now charges up the condenser. The result

is that at the end of a group of oscillations received in the aerial the plate of the condenser connected to the grid is left at a higher negative potential than it was at the beginning of the signal. The resistance R allows this charge to drain away to the filament so that the grid potential returns to its previous value ready for the next group of oscillations.

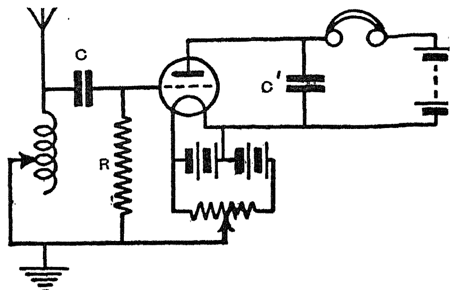


Fig. 88.

It will be seen, therefore, that each time a group of oscillations is received in the aerial the grid is left with a large negative potential which gradually returns to the normal value; in other words, the potential of the grid varies at the same rate as the

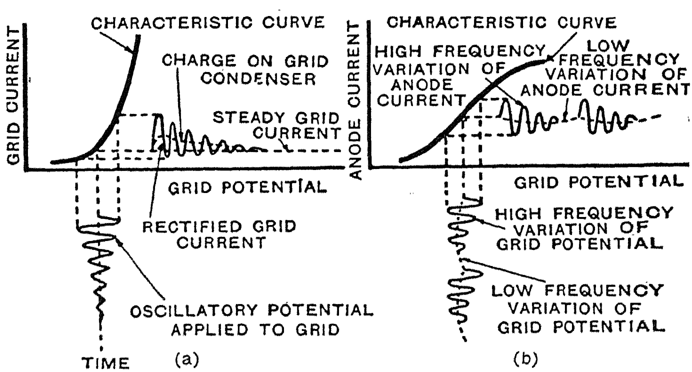


Fig. 89.

frequency of the incoming groups of oscillations, which is equal to the spark frequency if the oscillations are produced by a spark at the transmitting station.

The effect of this variation of the grid potential is, therefore, to produce a variation of the same frequency in the anode current, thus producing a note in the telephones. The high frequency variation in the potential of the grid during the time each group of oscillations is being received, produces a corresponding high frequency variation in the anode current. This high frequency current passes through the condenser C′, and not through the telephones. The changes which occur in potential and current are shown in Fig. 89.

By arranging the values of the condenser C and the resistance R, it is usually found in practice that the potentiometer can be omitted, as the normal potential of the grid when receiving signals is then of the required value.

The cumulative grid rectification method is much more sensitive than anode rectification or rectification by means of a crystal or two electrode valve. The conditions should be such, however, that the fairly straight portion of the anode characteristic is utilised, otherwise a certain amount of anode rectification is introduced which opposes the telephone current produced by the cumulative grid rectification if the lower bend of the curve is used.

65. Valve used as Amplifier.—If, instead of working under the conditions represented by the curved portions of the anode current-grid potential characteristic, the conditions are made to correspond to the straight portion (Fig. 90), no rectification will occur if the grid potential does not vary sufficiently to move off the straight portion of the curve. Under these conditions, however, the change in anode current is a maximum for a given change in grid potential. Since large variations in the anode current are caused by small variations in the grid potential, even though the grid current is very small, the valve acts as a simple amplifier under these conditions.

As the electrons are moving at a very high velocity, any change in the potential of the grid is followed practically instantaneously by a corresponding change in the anode current; the time lag is, therefore, negligible. Any change in the anode current causes a corresponding change in the

anode voltage owing to the drop in the telephones or in whatever takes their place. The amplification obtained is, therefore, the ratio of the change in the anode voltage to the change in grid voltage. This ratio is called the **amplification factor** of the valve. No tuned circuits are involved in the arrangement shown in Fig. 90, and the valve can, therefore, be used as an amplifier of alternating E.M.F.'s of any frequency, or as an amplifier of steady E.M.F.'s.

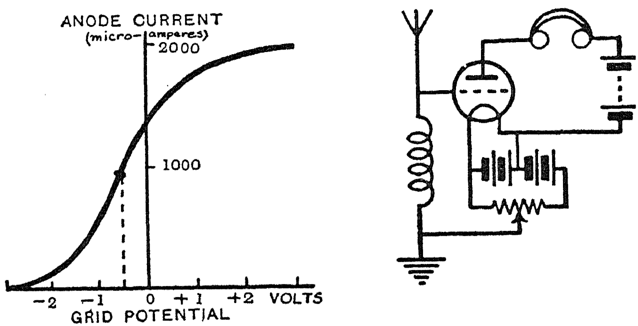


Fig. 90.

It will be seen that the steeper the anode characteristic curve the greater will be the amplification.

After amplification high frequency oscillations produced by electromagnetic waves have to be rectified in the ordinary way before intelligible signals are produced (see Chapter III.).

Before rectification the received oscillations may be amplified several times by using valves **in cascade.** This means that the amplified oscillations in the anode circuit of the first amplifying valve are transferred to the grid circuit of a second amplifying valve, and are again amplified by the second valve. Several valves may be used in this manner for amplifying the high frequency oscillations, and after rectification the low frequency oscillations may be amplified in a similar manner. The various methods of high and low frequency amplification are described in Chapter VI.

66. Use of Reaction or Retroaction.—When a valve is being used as an amplifier, a resistance or an inductance or a tuned circuit may be connected in the anode circuit, and the variation in anode voltage will occur across whichever of these is used. The tuned circuit can be used in order to make the arrangement most efficient for a given wave-length.

The energy required for producing the oscillatory current in the anode circuit is supplied by the anode battery, whereas the energy in the grid circuit producing the oscillations to be amplified, when the valve is being used for amplification of received signals, is obtained from the incoming waves, and is of extremely small magnitude.

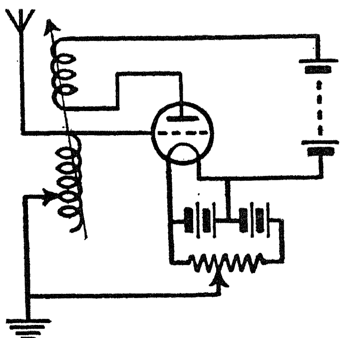


Fig. 91.

Much of the received energy in the grid circuit is dissipated in the resistance of the grid circuit, and is, therefore, not available for amplification. If, therefore, the energy dissipated can be made good by supplying sufficient energy to the grid circuit from the anode battery, the change in oscillatory voltage in the anode circuit will be much greater. This can be obtained by the arrangement shown in Fig. 91.

An inductance in the anode circuit is coupled to the inductance in the grid circuit, and, therefore, the oscillatory P.D. across the anode inductance, produced by the amplification of the incoming signals, induces an oscillatory P.D. across the inductance in the grid circuit. By suitable arrangement of the coupling and the value of the anode inductance this induced oscillatory P.D. can be made in phase with the P.D. produced by the incoming signals, and can be made to supply the energy dissipated in the grid circuit. The variation in grid potential will, therefore, be increased, and this causes an increased variation in the anode current.

Capacity or resistance coupling between the anode and

grid circuits can also be used to produce the same effect (see Chapter VI.). The use of coupling between the output side of a valve and circuits supplying energy to the input side, is called **reaction** or **retroaction** or **back coupling.**

67. Valve used as Generator of Oscillations.—Now suppose the reaction used in the arrangement shown in Fig. 91 be increased so that the energy supplied to the grid circuit from the anode battery is greater than the energy required to make up the losses in the grid circuit. Oscillations will now be set up in the grid circuit and maintained by energy from the anode circuit. Even when no energy is being received from the aerial circuit these oscillations will be maintained.

A valve can therefore be used in this manner to produce oscillations for transmitting purposes, or for use in the reception of continuous oscillations by the heterodyne method.

The use of valves for transmission purposes is treated more fully in Chapter VII., and the use of valves in receiving circuits is dealt with in Chapter VI.

68. Design of Thermionic Valves.—As a result of the very large amount of experimental work that has been carried out in connection with the development of thermionic valves, it is now possible to predict fairly accurately the characteristic curves of a valve of given dimensions.

The effects of different sizes and types of filaments, grids, and anodes, and their relative positions, and the degree of exhaustion, etc., are now fairly well understood and can be calculated for the standard types of valves.

Knowing the purpose for which a valve is required the design can be arranged to give the required characteristic curves. Difficulties occur of course in constructing reliable valves of new types, due largely to mechanical and electrical troubles such as the provision of suitable supports for the filament to prevent vibration and breakage, adequate insulation to prevent leakage between electrodes, suitable connections to electrodes to carry fairly heavy currents and maintain the high vacuum in large transmitting valves, etc.

Typical valves for various purposes are described briefly in this chapter, but their detailed design is beyond the scope

of this book. The reader is referred to text-books on thermionic valves and to the publications of the various scientific bodies for further information.*

69. Construction of Valves.—The filament of a valve usually consists of a straight wire or single loop of tungsten, thoriated tungsten, or platinum coated with lime. Tungsten is usually employed for transmitting and rectifying valves, and thoriated tungsten for receiving valves. Each end of the filament is brought through the wall of the valve, the method depending on the type of valve.

The grid may consist of tungsten, nickel or molybdenum in the form of a spiral or fine mesh cylinder surrounding the filament, or it may consist of a perforated metal plate or flat grid on one or both sides of the filament. In the latter case the two plates or grids are connected together. In all cases one lead only is taken through the wall of the valve.

The anode (sometimes called the sheath or plate) is usually made of nickel, molybdenum or tungsten in the form of a cylinder surrounding the grid if the latter is cylindrical, or in the form of a plate if the grid is flat.

The wall of the valve is made of glass for receiving valves and low power transmitting valves, and is made of silica or metal for high power valves where the heat dissipated would cause glass to melt. If metal is used it is necessary to employ a vacuum pump to keep the valve exhausted when in use, as a metal valve cannot be made absolutely airtight.

Various types of valves are described briefly on succeeding pages.

70. Audion Valve.—Lee de Forest's original type of three electrode valve was known as an audion valve. It had a tantalum filament and a nickel wire grid on one or both sides of the filament, and an anode consisting of one or two nickel plates connected together. Connection was made to the filament by screwing into a metal holder, and the anode

* *E.g.*, B. S. Gossling: "The Development of Thermionic Valves for Naval Uses," *Journal I.E.E.*, Vol. 58, p. 670, August 1920. G. Stead: "The Short Tungsten Filament as a Source of Light and Electrons," *J.I.E.E.*, Vol. 58, p. 107, Jan. 1920.

and grid connections were brought out as flexible leads at the top of the valve (Fig. 92). Filament currents of $\frac{1}{2}$ to $\frac{3}{4}$ of an ampere were used, and anode voltages of 15 to 100.

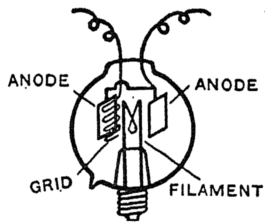


Fig. 92.

The audion valve was a soft valve, very difficult to reproduce in quantities, but was practically the only type of valve available in the early part of the war. It was a good amplifier, though erratic, but other valves were found to be better detectors, and the audion was often used as an amplifying valve with another type of valve as detector.

71. Round Valve.—One of the early types of valve was that due to H. J. Round. It had a vertical filament of platinum treated with lime, and had a grid of nickel gauze of cylindrical shape. The anode was an aluminium or nickel cylinder. Connection was made to the filament by a brass screw cap (Fig. 93), and the anode and grid connections were brought through the side of the valve.

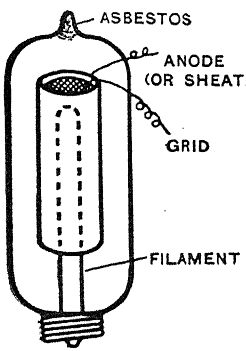


Fig. 93.

A special feature of the Round valve was the provision made to increase the softness of the valve when necessary. Asbestos was contained at the top of the valve, and on being heated it released air and so increased the softness. A coil of wire carrying a current was usually employed to heat the asbestos. The filament current was as much as 3 amperes at 4 volts, and the anode voltage varied from 25 to 400 depending on the softness of the valve.

72. White Valve.—The White valve (Fig. 94) was another early type of valve used during the war. It had a platinum filament coated with lime taking about 2·8 amperes at 6 volts.

The connections were made to the filament by means of an ordinary bayonet cap. The grid was a perforated copper disc connected to the brass casing of the bayonet cap. The anode was a copper disc coated with mercury and connected to a terminal at the top of the valve. The anode voltage required was usually 25 to 75, but up to 300 was used in some cases.

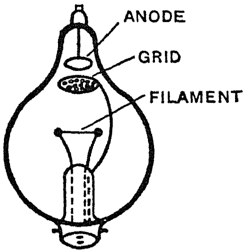


Fig. 94.

73. The Pliotron.—The first hard valve to come into prominence was the Pliotron, due to Langmuir, which was used for both reception and transmission.

The filament was of hairpin shape supported by a small spring at one end from a glass framework (Fig. 95) which

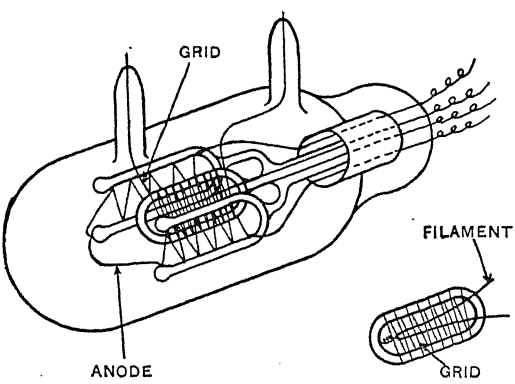


Fig. 95.

supported the grid. The latter consisted of fine tungsten wire wound round the glass framework. The anode was composed of fine wire supported on glass stems outside the grid.

74. French Valve.—The valve which came to be used almost universally towards the end of the war for receiving purposes was a hard valve due largely to the French. This type of valve and slight modifications of it are probably still the most commonly used.

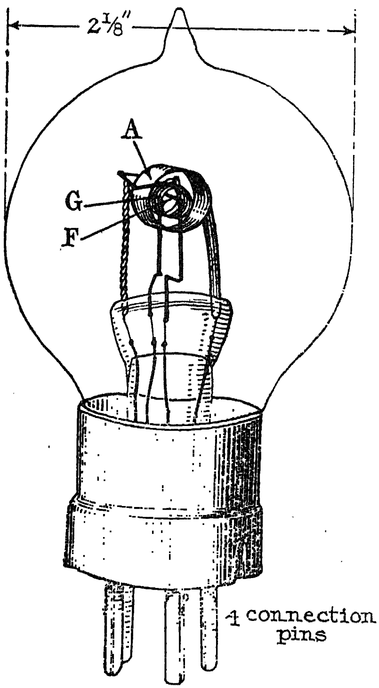


Fig. 96.

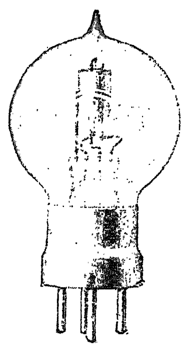


Fig. 96*a*.

The French valve has a straight filament of tungsten, a grid of nickel wire wound in a coarse spiral, and a cylindrical nickel anode (Fig. 96). All the connections are brought out to split pins in the base, and these pins are unequally spaced to prevent wrong connection when the valve is placed in the

holder. The filament current is about 0·65 amperes at 4 volts, and the normal anode voltage is 25 to 75, although 100 to 150 may be used.

The Army R valve is practically the same valve produced in England in large quantities towards the end of the war, and is a good all round valve for use as a detector, amplifier, or oscillator. Valves of this type are used to a great extent for the reception of "broadcasting." Fig. 96*a* shows the Mullard R.A. valve, which is an improved form of this type of valve.

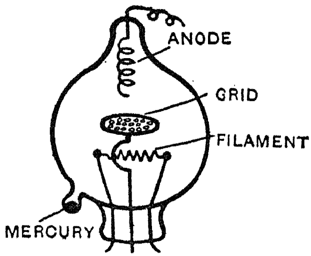


Fig. 97.

75. Lieben Valve.—An early type of transmitting valve, known as the Lieben valve, was of German origin. It stood about a foot high, and had a filament of platinum strip covered with calcium and barium oxide. The anode was a coil of aluminium, and the grid was a perforated aluminium disc (Fig. 97).

Mercury vapour was present inside the valve, and the softness could be increased by heating a small quantity of mercury contained in a small

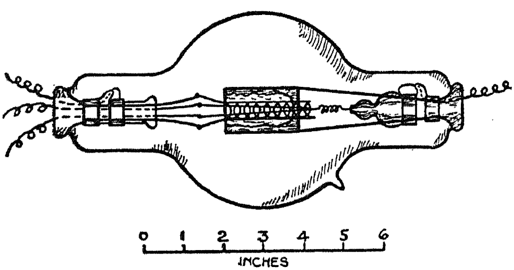


Fig. 98.

pocket at the bottom of the valve. The filament voltage was about 30, and the anode voltage about 300.

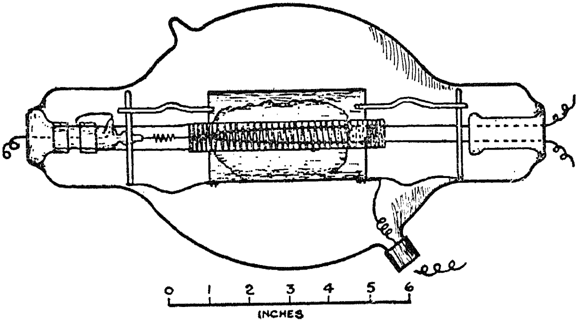


Fig. 99.

76. TI and T4A Valves.—One of the first types of transmitting valves manufactured in quantity was the TI valve developed for the British Navy in 1917 (Fig. 98). By omitting the grid the first Naval power-rectifying valve was produced.

A later type of Naval valve was the T4A valve (Fig. 99), rated at 400 watts dissipation in the valve, with an output of 600 watts oscillatory power. The efficiency was, therefore, 60 per cent. Anode voltages of about 3,000 were used.

77. Silica Valves.—H.M. Signal School, Portsmouth, in conjunction with S. R. Mullard, of the Mullard Radio Valve Co., Ltd., have developed transmitting valves with silica envelopes, instead of glass, for the British Navy. Silica valves of 2 and 4 kW rating are now being produced in large quantities, and valves capable of an output of 21 kW have been produced.

Fig. 100 shows a typical silica valve capable of being opened to renew the filament when necessary, and then sealed up again and re-exhausted.

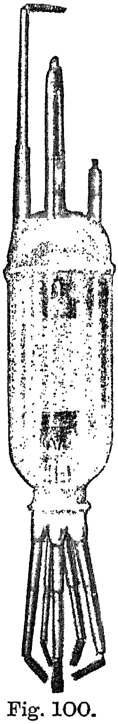


Fig. 100.

78. Metal Valves.—Many attempts have been made to produce high power, water-cooled, transmitting valves with metal containers instead of glass or silica. It is found to be necessary, however, to exhaust metal valves continuously while working, as air leaks through the container. Additional apparatus, such as vacuum pumps, is therefore required.

A 10 kW valve of this type, known as the Holweck valve, has been in use for some time at the Eiffel Tower.* At the Post Office station at Northolt the Western Electric Co.'s water cooled valves have delivered over 14 kW per valve to the aerial.

79. Receiving Valves with Low Filament Consumption.—Since the introduction of broadcasting there has been a great demand for receiving valves suitable for use as detectors, amplifiers, or oscillators, and requiring low filament current and voltage. Several valves of this type, known as **dull emitters,** because the filament is only at a dull red heat, are now on the market.

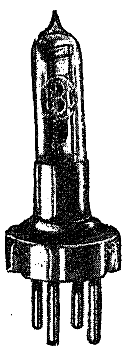


Fig. 101.

The filaments of dull emitter valves are usually coated with thorium oxide to increase the emission, but filaments of tungsten with an alloy of sodium and potassium have been found to give good results.† Fig. 101 shows the Mullard Wecovalve, which takes 0·25 amps. at 0·8-1·1 volts and requires an anode voltage of 30-50 when used as an amplifer, and 15-25 when used as a detector. A single dry cell may be used to supply the filament.

80. The Dynatron and the Negatron.—An ordinary thermionic valve produces an increase of anode current when the anode voltage is increased. In two special types of valves, known as the dynatron and negatron respectively,

* See *Wireless World and Radio Review*, Vol. XIII., No. 15, January 9th, 1924.

† See *Journal of the American I.E.E.*, January 1924.

the opposite effect occurs, and these devices act as negative resistances, and can be used as amplifiers and generators of oscillations, etc.

The dynatron has a filament of fine tungsten wire in the form of a spiral, an anode consisting of either a perforated metal cylinder or a thick wire spiral, and a third electrode, known as the plate or target, consisting of a metal cylinder surrounding the anode and quite close to it (Fig. 102).

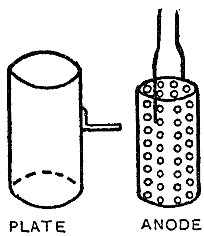


Fig. 102.

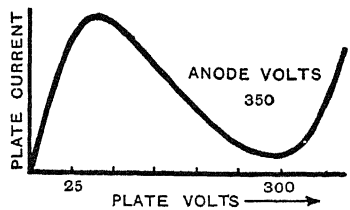


Fig. 103.

The anode is kept at a higher potential than the plate, the former perhaps being 350 volts and the latter 250 volts. At these voltages some of the electrons flowing from filament to anode shoot through the perforated anode and strike the plate, causing electrons to be liberated from the plate and flow to the anode, which is at higher potential. This secondary emission may be made to produce a current greater than that due to the electrons flowing to the plate, by increasing the plate voltage, thus causing the device to act as a negative resistance. Fig. 103 shows a typical characteristic curve of the relation between plate voltage and current in a dynatron.

Up to a plate voltage of about 25 the dynatron acts as an ordinary unsaturated three-electrode valve; from about 25 volts to 300 on the plate it acts as a negative resistance until the voltage approaches that of the anode, and in consequence the electrons emitted from the plate commence to return to it.

In the negatron an additional anode, called the **diversion anode** is introduced into a three electrode valve, the two

anodes being one on each side of the filament with the grid between the filament and the diversion anode. Normally the anode current is at saturation value, and divides between the two anodes, but an increase in potential of the main

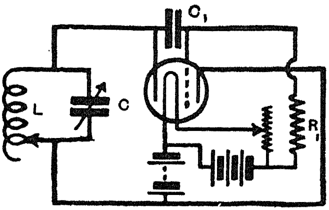


Fig. 104.

anode causes an increase in the potential of the grid, and this causes an increase in the current to the diversion anode at the expense of the main anode. Fig. 104 shows the method of connecting the negatron to produce oscillations in the circuit LC. C_1 and R_1 form the grid leak to keep the grid normally at a potential about zero.

CHAPTER VI.

RECEIVING CIRCUITS, AMPLIFIERS, AND NOTE MAGNIFIERS.

81. Recent Developments.—Within the last few years enormous progress has been made in the development of receiving apparatus for wireless telegraphy and telephony, as well as in the development of transmitting apparatus.

High frequency oscillations induced in a receiving aerial, even if they are of extremely small amplitude compared with the oscillations necessary for detection by means of the apparatus available less than ten years ago, can now be detected quite readily, and, in fact, can be made to produce sounds sufficiently loud to be heard by large numbers of people. The signals received may even be transmitted over miles of ordinary telephone land line and then re-transmitted in the form of electromagnetic waves through the ether. Speeches, operas, plays, and sounds of all descriptions can be picked up by means of special microphones, and amplified and transmitted to all parts of the world, sometimes by wireless telephony, sometimes by ordinary land telephony, and sometimes by both.

Morse signals of sufficient strength to enable them to be transmitted over land lines to places miles away can now be produced at a receiving station from a smaller amount of energy received in the aerial than that required to produce audible signals in a pair of telephones by methods in use only a few years ago.

In spite of the presence of electromagnetic waves in the ether, transmitting energy which is capable of producing sounds of all kinds in receiving apparatus, the design of the latter, in conjunction with the design of transmitting

apparatus, has made it possible to receive only the particular kind of waves required, in spite of the proximity and power of stations transmitting other waves.

The development of selective amplifiers of high and low frequency currents is the most important factor in the realisation of all these now commonplace wonders. Not only are amplifiers an essential part of the wireless telegraphy and telephony of to-day, they have become of great importance in the transmission of speech by ordinary line telephony over long distances.

82. Requirements of a Receiving Circuit.—Before discussing the different kinds of amplifiers of high and low frequency voltages and currents, the requirements of the receiving circuit for any particular purpose will be briefly considered. An excellent receiving circuit for one purpose may be of no use in other cases.

The term "receiving circuit" is used throughout this chapter to denote the complete receiving circuit from the aerial circuit to the telephones or other apparatus used to make the signals intelligible to the senses.

83. Wave-length.—Probably the most important requirement to consider is the wave-length or wave-lengths for which the circuit is required. In practically all cases the circuit is required for receiving waves of more than one wave-length, but it is very often required to work for the most part on one wave-length only. If the latter is the case, it is usually necessary for the circuit to be most efficient for that particular wave-length. If rapid tuning is required to change quickly from one wave-length to another a complicated circuit cannot be used, and efficiency may have to be sacrificed.

84. Selectivity.—The degree of selectivity required depends on the power, proximity, wave-length, and accuracy of tuning of transmitting stations in the vicinity of the station where the receiving circuit is to be employed. For naval and military purposes, where large numbers of transmitting sets are quite close together, selectivity may be of the utmost importance.

85. Sensitivity.—The distance from stations whose transmissions it is desired to receive, the nature of the intervening surface of the earth, the power of these stations, the nature of the receiving aerial, all have to be considered in determining the sensitivity of the receiving apparatus. If the conditions are such that the energy received in the aerial circuit is very small, high frequency amplification is necessary before the signals are rectified, otherwise rectification will be inefficient (see page 129). The amount of amplification required will depend upon the energy received. If strong signals are required, the low frequency current produced after rectification of the high frequency oscillations will require amplification in order to give sufficient energy to work a loud-speaking telephone or other apparatus, or for transmission over land lines.

86. Stability.—Where it is necessary for the receiver to be absolutely reliable, stability is essential. By this is meant that the sensitivity must be capable of being controlled by the operator, and must not be liable to be upset by the reception of very strong signals, or "atmospherics," or by small changes in stray capacity, *e.g.* those due to movement of the operator or leads. The use of much reaction or back-coupling, to increase sensitivity, must be avoided to prevent strong oscillations being generated in the circuit by the receiving valves, especially if spark signals or speech are to be received.

Sensitivity should, therefore, be increased by increasing the number of valves, instead of using much reaction, if stability is essential.

87. Continuous Waves.—If the reception of continuous waves is required, the set will have to be capable of producing local oscillations. If spark or speech reception is required in addition, the control of the oscillations must be easy, otherwise the circuit will be unstable.

88. Interference by Local Oscillations.—If the set is being used to receive continuous waves, or is liable to oscillate owing to its being unstable, continuous waves will be transmitted if the local oscillations are allowed to set up

oscillations in the aerial circuit. If these are liable to cause interference with other receiving sets in the neighbourhood the receiving circuit should be arranged to prevent this. For the reception of C.W. a separate circuit can be used for the production of the local oscillations, or the heterodyning action made to occur in one of the intervalve circuits distant from the aerial circuit to decrease the amplitude of the oscillations induced in the aerial.

89. Elimination of Atmospherics.—If the circuit is to be used where atmospherics are plentiful, special precautions are required to cut them out. These precautions are most important in the case of receiving stations in the tropics. The elimination of atmospherics is one of the most important problems still requiring solution. A great deal of progress has been made, but much work remains to be done before a complete solution can be obtained.

90. Prevention of Distortion.—For the reception of wireless telephony, especially music, it is essential that distortion of the signals should be reduced to a minimum, otherwise faithful reproduction of the transmitted speech or music will be impossible. In the case of wireless telegraphy the prevention of distortion of the signals is not so important, as Morse signals can be read even if they are slightly distorted.

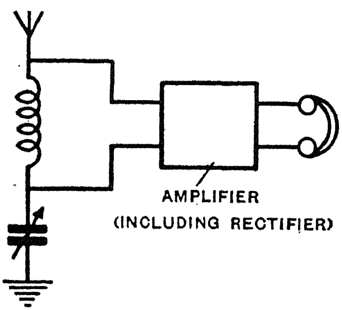


Fig. 105.

91. The Tuner Portion of a Receiving Circuit.—An essential part of a receiving set is a circuit (or circuits) tuned to the frequency of the waves to be received, in order that oscillations of sufficient magnitude to render them capable of detection may be produced, except in the case of powerful stations transmitting over short ranges.

A single tuned circuit, the aerial circuit, may be used,

with the detector connected directly to it. An amplifier may also be used if necessary (see Fig. 105).

Tuning may be obtained by using either a variable inductance or condenser, or both. Usually a variable inductance is used for approximate tuning, and a variable condenser, connected either in series or in parallel with the inductance, is used for fine tuning. The position of the condenser depends on its value relative to the capacity of the aerial, and upon whether a large range of wave-lengths is required to be covered by simply varying the condenser whilst using one value of inductance.

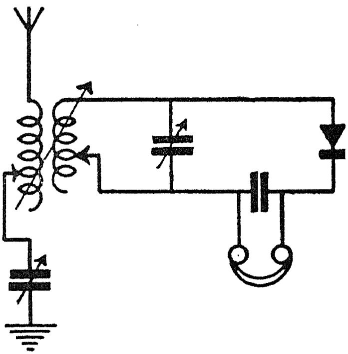


Fig. 106.

A circuit of this nature is not very selective, as oscillations may be induced in the aerial circuit by waves of a slightly different frequency.

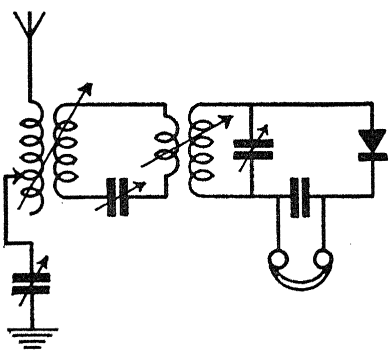


Fig. 107.

Except in cases where there is likely to be no interference from stations transmitting on different wave-lengths from the one to be received, an additional tuned circuit is usually introduced as shown in Fig. 106. A crystal detector is shown for simplicity.

Even if forced oscillations are set up in the aerial their effect on the tuned secondary circuit is much less than that of oscillations of the same frequency as that of the aerial circuit and the secondary circuit.

If increased selectivity is required the number of intermediate circuits may be increased (Fig. 107), but usually one circuit in addition to the aerial circuit is found to be sufficient, and additional circuits mean increased losses and more complicated tuning. These circuits are usually distinct from any detector or amplifier that may be used, and the various tuning inductances and condensers are often assembled in a separate box called the "tuner."

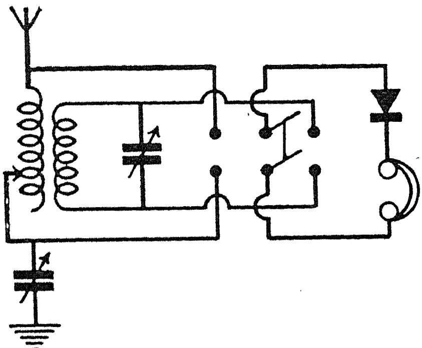


Fig. 108.

An amplifier used with a tuner covering a certain range of wave-lengths is usually designed for the same range of wave-lengths and therefore introduces additional selectivity.

In some receivers where a tuned secondary circuit is used, a change-over switch is introduced to enable the detector to be put straight into the aerial circuit to reduce the selectivity when attempting to pick up signals. Once the signals have been received in this "stand-by" position, as it is called, the switch can be changed over to put the detector across the tuned secondary in order to cut out signals which would otherwise cause interference (Fig. 108).

Another switching device is often used to enable the aerial condenser to be put in series with the aerial when receiving short waves and put in parallel when receiving longer waves.

Interfering signals are often cut out by using what are called **acceptor** and **rejector** circuits. The circuit shown in Fig. 109 (*a*) will allow the passage of oscillations of the same frequency as that of the circuit, but it has a very large impedance to oscillations of any other frequency, especially if the inductance is large compared with the capacity.

On the other hand the circuit shown in Fig. 109 (*b*) allows

the passage of oscillations of a frequency different from that of the circuit but has a very large impedance to oscillations of the same frequency. The former circuit is often referred to as an acceptor circuit and the latter as a rejector circuit. They are simply cases of series resonance and parallel resonance respectively as described in Chapter I. It is important that the resistance should be extremely small in both cases.

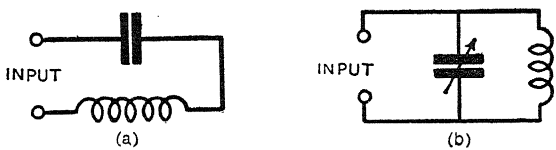


Fig. 109.

Fig. 110 shows the use of a parallel rejector circuit to reduce interference.

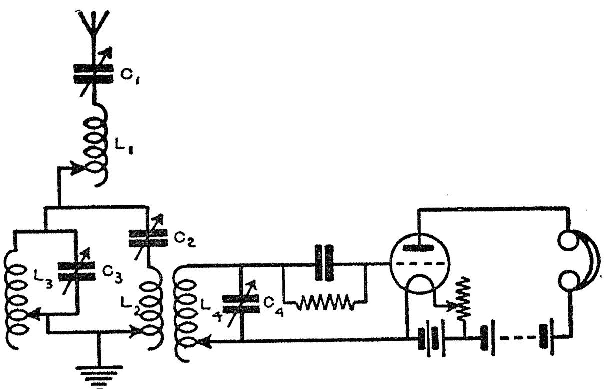


Fig. 110.

The acceptor circuits C_1L_1 and C_2L_2 are each tuned to the frequency of the waves to be received. The rejector C_3L_3 is also tuned to the same frequency. The oscillations due to the signals required have an easy path via $C_1L_1C_2L_2$ and

therefore induce oscillations in the tuned secondary circuit C_4L_4. The rejector circuit C_3L_3 has a large impedance to the desired oscillations but provides an easy path to any oscillations of other frequencies set up in the aerial, thus preventing to a great extent the production of interfering oscillations in the tuned secondary. C_3 should be large compared with L_3 to give low impedance to oscillations of the non-resonant frequency.

A series rejector circuit can be employed for the same purpose, as shown in Fig. 111. In this case, however, the rejector circuit is tuned to the frequency of the interfering oscillations, and so prevents their formation, but provides a low impedance path for the desired oscillations.

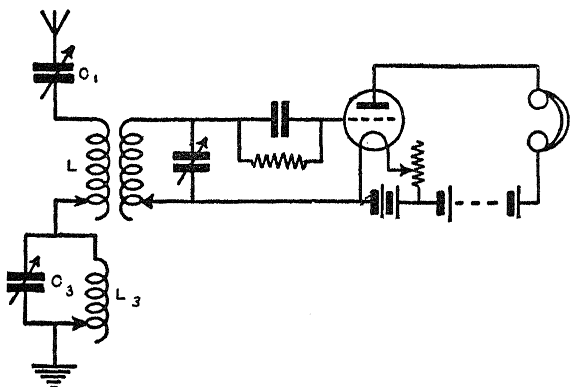


Fig. 111.

These methods reduce interference to a great extent, but, owing to the presence of a certain amount of resistance in the circuits, interfering oscillations are not cut out altogether.

A great improvement has been made by the introduction of reaction to reduce the damping, and this method is being adopted at the stations of the Imperial Wireless Chain, and has already been installed at several Government stations. Fig. 112 shows the method of using reaction with a parallel rejector circuit.

This method is being used to eliminate atmospherics, which are usually of low frequency, by the introduction of

low frequency rejector circuits. Fig. 113 shows the principle used. The L.F. signals produced after rectification are amplified by the low frequency amplifying valve, and pro-

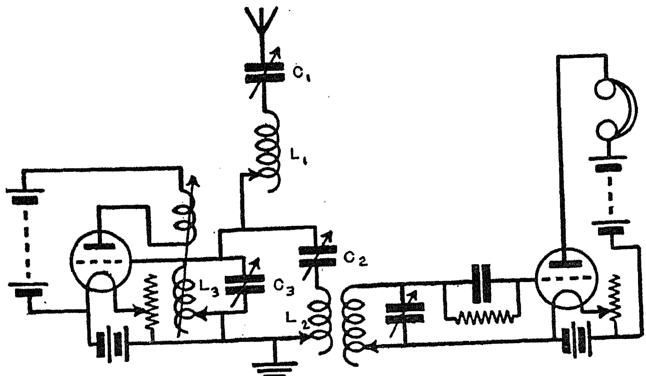


Fig. 112.

duce a note in the telephones. The latter are shunted by the low frequency rejector circuit CL, which is coupled back to the grid circuit, thus producing reaction which neutralises

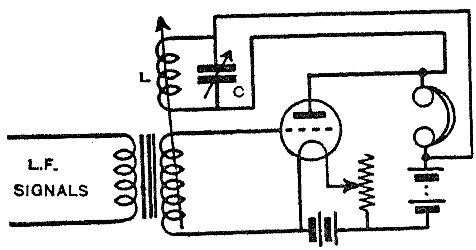


Fig. 113.

the damping of the circuit CL. Low frequency currents, produced by atmospherics or other interfering sources, thus pass through the rejector circuit, whilst the signals required pass through the telephones.

92. Rectifiers used with Amplifiers.—In the early days of amplifiers, consisting of only one or two valves, it was quite usual to employ a crystal for rectifying the oscillations, and at the present time there is a tendency to return to this method of rectification in cases where economy is required in the use of batteries, *e.g.* in many cases where receiving sets are used for the reception of broadcast wireless telephony.

When several amplifying valves are used, however, the addition of another valve for rectifying purposes is usually found preferable to a crystal detector, on account of ease in manipulation of the set as a whole, apart from any question of the relative efficiency of the two methods.

93. Cascade Amplifiers.—As shown in Chapter V., variations in potential can be amplified by a three-electrode valve, and the amplified variations in the potential difference across a resistance, inductance, or condenser in the anode circuit of the valve can be transferred to the grid circuit of another valve and amplified again. This operation can be repeated several times by adding more valves, and the arrangement is known as a cascade amplifier or multi-valve amplifier.

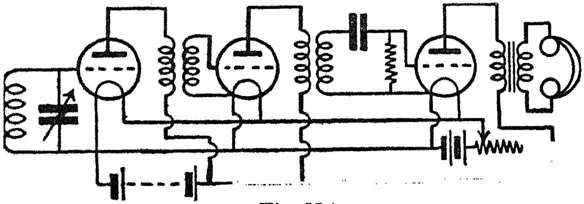


Fig. 114.

Such an arrangement is shown in Fig. 114, the oscillations being transferred from one valve to another by means of coupled inductances or inter-valve transformers, and the last valve used as a rectifier.

Common filament and anode batteries are used for all the valves, and no adjustment of grid potential is provided, the required positions on the characteristic curves being obtained by adjusting the filament current. Various methods used for coupling the valves are described on subsequent pages.

94. High Frequency and Low Frequency Amplification.—Amplification of received high frequency oscillations is used before rectification, as the efficiency of a rectifier which depends on the slope of its characteristic curve is greater for oscillations of large amplitude than for those of small amplitude (see page 60). Signals which would otherwise be too faint for detection can thus be received.

After rectification, the oscillations, which are now of low frequency, can be increased in magnitude once more by low frequency amplification, in order to produce a loud signal.

Low frequency amplification without high frequency amplification is not suitable for producing audible signals from very weak oscillations, owing to the small efficiency of the rectifier for weak oscillations. More low frequency amplification is required to produce a signal of a given strength from a received weak oscillation than the high frequency amplification required to produce a signal of the same strength from the same oscillation. In addition, where music or speech is being received, if iron is used in the circuits for low frequency amplification, distortion is more likely to occur.

It is usually preferable to use a certain amount of low frequency amplification, instead of increasing the high frequency amplification, on account of the increased tendency to set up local oscillations when not required when the number of high frequency valves is increased.

Amplifiers for high and low frequency oscillations are very similar in principle, the main difference being that iron can be used, and is, in fact, necessary where transformer coupling is used, in low frequency amplifiers.

95. Methods of Coupling Valves.—The following are the methods generally used for coupling valves used in an amplifier:—

(*a*) Inter-valve transformers.

(*b*) Tuned anode or rejector circuit.

(*c*) Resistance.

These methods are dealt with briefly in this chapter, an endeavour being made to give the chief features of each method.

96. Inter-valve Transformer Method of Coupling Valves.—Fig. 114 shows a typical amplifier using inter-valve transformer coupling. With this arrangement good amplification is not possible over much of a range of wave-lengths.

Owing to the natural capacity of the windings of each inter-valve transformer, tuned circuits of a fixed natural frequency are produced, and oscillations of this frequency only are efficiently amplified.

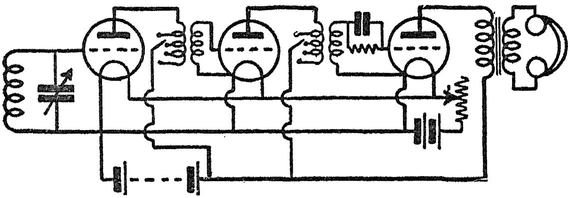


Fig. 115.

This difficulty can be overcome by providing one of the windings of each transformer with various tappings, as shown in Fig. 115. It is immaterial which of the windings of each transformer is arranged to have tappings, as there is little difference in the results.

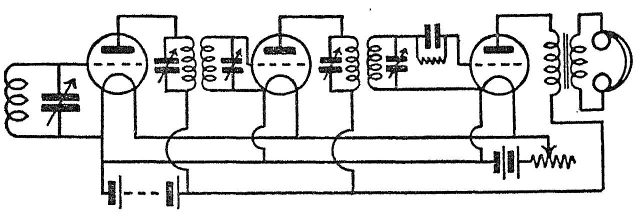


Fig. 116.

Another method of producing the same result is to connect a variable condenser across each or either of the transformer windings as shown in Fig. 116. This gives finer tuning than the arrangement shown in Fig. 115, but of course requires more adjustment and is seldom used with a condenser across each winding for this reason.

Transformer coupling is used for both high and low frequency amplifiers, but in the latter case the transformers are designed for one range of frequencies only, as no variation is required. Low frequency transformers have iron cores to give the required coupling at the low frequencies.

97. Tuned Anode Coupling.—A method which has been largely adopted recently, especially for the reception of wireless telephony, is the tuned anode or rejector circuit method of coupling valves.

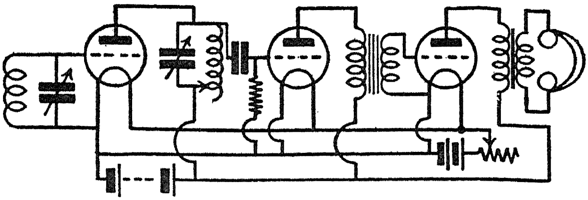


Fig. 117.

Fig. 117 shows tuned anode coupling between the amplifying valve and the detecting valve, and low frequency transformer coupling between the latter and the low frequency amplifying valve.

Tuned anode coupling gives a very selective amplifier which can be readily adjusted to any wave-length covered by the variable condenser and inductance forming the tuned anode.

98. Resistance Coupling.—The resistance method of coupling valves is the simplest method used, but is not very satisfactory for wave-lengths below 1,000 metres owing to the importance of stray capacities at high frequencies. It is very satisfactory for low frequency coupling as it is aperiodic; consequently it is largely used in note-magnifiers. A typical resistance coupled low frequency amplifier or note magnifier is shown in Fig. 118, the first valve acting as the detector.

The resistances R transfer the low frequency variations of voltage from the anode circuit of one valve to the grid circuit of the next valve through the condensers C. The function of these condensers is to insulate the grids from the high

voltage supply to the anodes, and their value is immaterial provided it is sufficiently large to pass the low frequency impulses. The resistances *r* are of the order of a megohm and act as grid leaks and maintain the grids at a suitable potential.

When resistance coupling is used for high frequency amplifiers special resistances are used with low capacity to ensure the high frequency oscillations passing through the resistance.

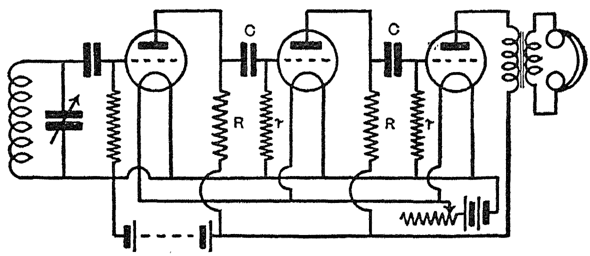


Fig. 118.

99. Reaction or Back Coupling.—In all amplifiers, especially those for high frequency, reaction or back coupling is present to a certain extent, either intentionally or unintentionally.

In Chapter V. it is shown how amplification can be increased by using reaction, the effect of which is to reduce the damping on the input side of the amplifier, and which therefore increases the amplitude of the oscillations.

Too much reaction causes the generation of oscillations which interfere with the reception of speech or spark signals, and which are only required for C. W. reception.

Even where no provision is made for reaction there is usually sufficient coupling between the output and input sides of an amplifier to produce a certain amount of reaction, especially at very high frequencies. It is therefore extremely important that an amplifier should be designed to have as little stray back coupling as possible, otherwise it will be unstable, and that the amount of reaction should be easily adjustable so that maximum amplification can be obtained where necessary without danger of oscillations being produced.

Inductive, capacity, and resistance reaction can be employed either together or separately; it is very difficult, however, to avoid all capacity reaction, and resistance reaction is present to a certain extent in multivalve amplifiers using a common anode battery for all the valves.

A circuit using reaction is often referred to as a **regenerative circuit.**

100. Inductive Reaction.—The most common method employed for controlling the reaction in an amplifier is that employing inductive coupling. This coupling may take place between any of the anode circuits of a multivalve amplifier and the aerial circuit or tuned secondary circuit or the grid circuit of any of the preceding valves. If a tuned anode is used reaction is very often employed between this circuit and the anode circuit of one of the succeeding valves as shown in Fig. 119.

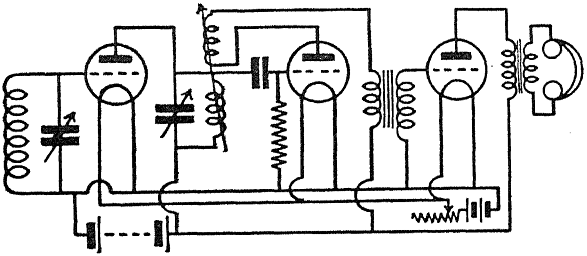


Fig. 119.

This method is very largely adopted where a three valve amplifier is used, in which the first valve is used for high frequency amplification, the second as a detector, and the third as a low frequency amplifier.

Inductive reaction in which the reaction coil is coupled to the secondary circuit and of course partially to the aerial circuit, is shown in Fig. 120. The disadvantage of this method is that if local oscillations are set up they may cause a large amount of interference to other stations in the same locality owing to radiation from the aerial. With the arrangement shown in Fig. 119, however, the oscillations set up in the aerial circuit are of smaller magnitude, as the majority

of the oscillations flow round the circuit on the output side of the first valve.

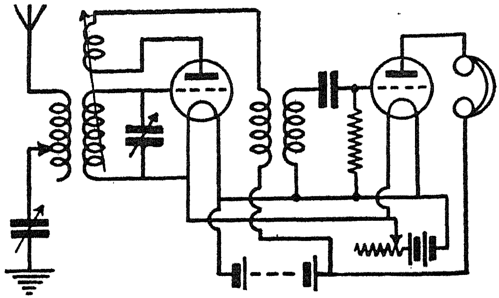


Fig. 120.

Inductive reaction is the method generally used, as it can be easily controlled, by altering either the inductance of the reaction coil or the coupling between this coil and the circuit to which it is coupled. The connections must be reversed if the coil is put in the anode circuit of the next valve owing to the difference in phase of the oscillations in the anode circuits of the two valves.

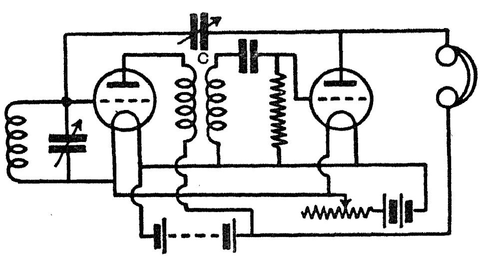


Fig. 121.

101. Capacity Reaction.—Capacity reaction is always present to some extent in amplifiers owing to the internal capacity between the anode and filament of a valve and to stray capacities. Fig. 121 shows an amplifier with capacity reaction. The condenser C enables the anode oscillations of

the second valve to affect the grid of the first valve. It must be connected between the correct valves in multivalve amplifiers, otherwise its effect will be 180° out of phase.

102. Resistance Reaction.—Resistance reaction has not yet found much application, but it may occur in mutivalve amplifiers with a common anode battery.

The oscillations in the anode of one valve cause a corresponding variation in P.D. across the resistance of the anode battery, and this is transferred to the anode circuit of the other valves. As the anode of a valve is connected to the grid of the next valve by a condenser in resistance coupled amplifiers and in those with tuned anode coupling, these oscillations are transferred to the grid and so reaction is produced.

103. Grid Control to Prevent Self-Oscillation.—Where reaction is employed in an amplifier to produce maximum amplification of spark or I.C.W. signals or speech, the tendency to self-oscillation is controlled very often by controlling the grid potential of one or more of the valves. By making the potential of the grid more positive with respect to the filament the effective resistance of the circuit is increased, and the amplification due to the valve is also usually slightly decreased, thus decreasing the tendency to oscillate. A potentiometer across the filament battery is generally used for this purpose.

104. Filament Control.—For the sake of simplicity it is not usual to control the filament of each valve separately to obtain the best point on the characteristic curve of each valve. Present day valves of the same type are fairly consistent in their behaviour and the general practice is to provide one filament rheostat for the high frequency amplifying valves, one for the detecting valve, and one for the low frequency amplifying valves, except in amplifiers of three or four valves, in which case a single filament rheostat is very often used.

105. Amplifiers Used for C.W. Reception.—It has been shown how continuous waves can be received by superposing oscillations of a slightly different frequency. Amplifiers

capable of producing self-oscillations can therefore be used for C.W. reception without any other source of oscillations being required. The circuit in which the local oscillations are produced, and in which the received oscillations are present, is slightly out of tune with the received oscillations, thus causing the local oscillations to have a slightly different frequency from that of the oscillations received.

This necessity for slightly mistuning the circuit reduces the efficiency for receiving long waves, but there is no sensible loss in sensitivity for short waves, as in the latter case the amount of a mistuning to produce an audible frequency is a very small percentage of the frequency of the incoming waves. Thus if the wave-length is 600 metres the corresponding frequency is 500,000 cycles per sec., and a difference in frequency of 1,000 will give a note whose frequency is 1,000. The amount of mistuning is therefore 1,000 in 500,000, *i.e.* 0·02 per cent.

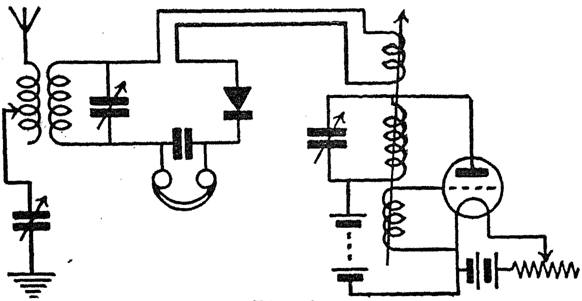


Fig. 122.

An amplifier for reception of C.W. is often called an **autodyne** or **autoheterodyne.** It has the advantage over a separate heterodyne of simplicity of adjustment, but has the disadvantage of less sensitivity for long waves and the greater likelihood of causing interference through the production of strong oscillations in the aerial circuit, which also reduce the amplification by causing the variation in grid potential of the last valves to be greater than the limits of the characteristic curves. The tendency is therefore to use separate heterodynes in many cases.

106. Separate Heterodynes.—A separate heterodyne for receiving continuous waves usually consists of a single valve arranged to produce oscillations of the required range of frequencies. Fig. 122 shows a heterodyne used with a crystal detector, and Fig. 123 shows the crystal replaced by a valve. Separate batteries are shown for simplicity, but common batteries can be used.

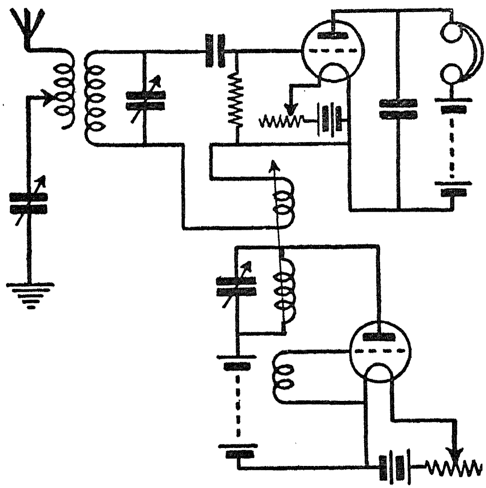


Fig. 123.

107. Super-regenerative Circuits. — Many attempts have been made to produce a stable circuit giving greater amplification than is normally obtained without the set oscillating. An amplification much greater than normal can be obtained with some of these circuits, but very careful adjustment is usually required. So far sufficient stability combined with simplicity has not been obtained to bring them into general use.

The principle of these **super-regenerative circuits,** as they are called, is the introduction of intermittent damping into the circuit to prevent the generation of oscillations, the intervals between these periods of damping being periods of

high sensitivity when the incoming oscillations are amplified by energy from the anode battery by means of a larger amount of reaction than can normally be used without generating oscillations. The frequency of the periods of damping is usually just above that of audibility.

In the method due to Armstrong the damping is introduced by a separate oscillating valve coupled to the circuit in such a manner that the oscillations produced by this valve oppose the received oscillations in the grid circuit of the amplifying valve and so reduce the tendency to oscillate. By the introduction of additional circuits the separate valve can be omitted and the amplifying valve made to act in both capacities.

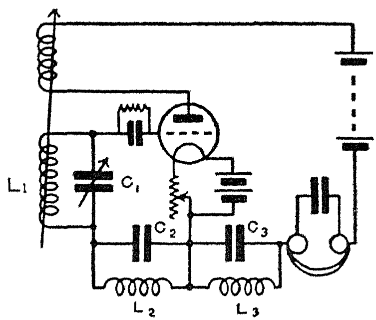


Fig. 124.

Fig. 124 shows one form of the Armstrong circuit using one valve only. The circuit L_1C_1 is tuned to the frequency of the signals to be received, and the circuits L_2C_2 and L_3C_3 are alike and tuned to the frequency required for damping.

A simpler method, due to another American named Flewelling, achieves the same result by the introduction of a condenser into the grid circuit. By suitable adjustment of the values of this condenser and the grid leak in particular, and of other parts of the circuit, this condenser can be made to block and free the grid of the valve at the rate of about 10 to 15 thousand times a second, which produces a shrill note that is almost inaudible. One form of the circuit is shown in Fig. 125.

The Armstrong and Flewelling circuits have been found to give excellent results in the reception of wireless telephony on short waves, but require very critical adjustment.

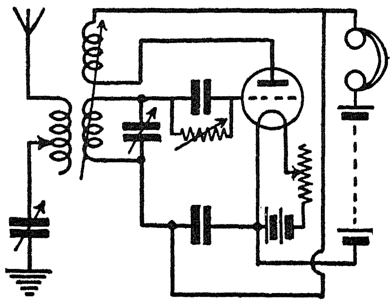


Fig. 125.

108. Limiting.—A method known as **limiting** is sometimes employed to enable weak signals to be read in the presence of strong interference by other signals or atmospherics.

One of the valves of an amplifier, usually the detecting valve, is adjusted so that the saturation value of its anode current is fairly low. This result is obtained by reducing the filament current of the limiting valve, which is provided with a separate filament rheostat. The effect on the anode current of the weaker signal to be received is usually reduced slightly owing to the change in slope of the characteristic curve, but the effect of the louder interfering signal is very much reduced, as the strength of any signal is now limited by the low saturation value of the anode current.

CHAPTER VII.

VALVE TRANSMITTING SETS.

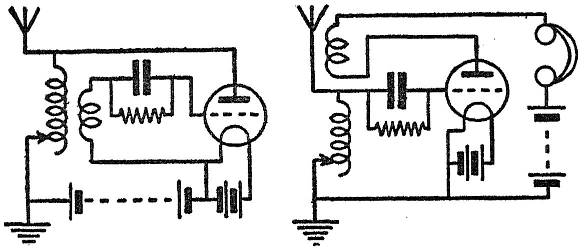
109. Introductory.—The use of the thermionic valve for producing high frequency oscillations for the transmission of wireless telegraphy and telephony bids fair to supersede all other methods so far employed.

The chief difficulty up to the present has been the small output that could be obtained from a thermionic valve, necessitating the use of a large number of valves in parallel and series where large oscillatory power was required. The complications involved in the use of a large number of valves meant that transmitting sets employing arcs or high frequency alternators were superior for large outputs, owing to their comparative simplicity.

The development of high power valves, however, has made rapid progress during the last few years, and now that valves are obtainable with outputs up to 10 kW, and others have been constructed to give as much as 25 kW (see Chapter V.), more and more high power stations are being fitted with valve sets. The Imperial Wireless Telegraphy Commission has decided in favour of valve sets for the high power stations to be constructed for communication throughout the British Empire.

For low and medium power sets valves are acknowledged to be the best on account of their simplicity, high efficiency (40 to 50 per cent. overall), the freedom from harmonics in the transmitted waves, and the ease with which they can be adapted for transmitting either continuous waves or interrupted continuous waves.

110. Simple Valve Transmitting Circuit.—The theory of the simple valve transmitting set is described in Chapter IV. Fig. 126 (*a*) shows a simple valve transmitting set which is essentially the same in principle as the circuit for a valve arranged for C.W. reception, as shown in Fig. 126 (*b*).



(*a*) Fig. 126. (*b*)

The only difference between the two circuits is that the tuned aerial circuit has been put in the anode circuit for transmitting purposes, as the maximum oscillations occur in the anode circuit. The aperiodic reaction coils shown in the two cases can be shunted by a variable condenser to give a larger range of wave-lengths, but the principle remains the same.

In order to prevent the filament being at a high potential above earth when the anode supply is at a high voltage, the usual practice, except in sets of low power, is to put the anode supply in parallel with the anode oscillatory circuit, as shown in Fig. 127. This arrangement allows the oscillatory component of the anode current to flow through the aerial circuit only, and only the steady anode current from the anode supply flows round the supply circuit. A high frequency choke coil is placed in series with the anode supply to prevent any high frequency current passing through the supply circuit.

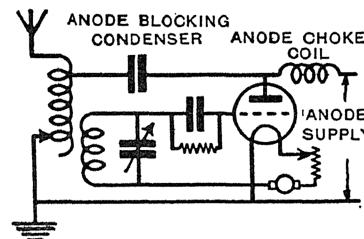


Fig. 127.

A condenser of large capacity is placed in the circuit

between the anode and the aerial circuit to prevent the anode supply from being short-circuited through the aerial circuit. This condenser must be of sufficient value to have negligible reactance to the high frequency oscillations.

The potential of the grid is maintained at the required value by a condenser in parallel with a grid leak.

The anode connection to the aerial circuit is made at different points of the aerial inductance, depending on the wave-length used. The position at which connection is made is often referred to as the **anode tapping point.**

The voltage between the anode tapping point and earth at any instant is equal to the voltage between anode and filament. If the inductance between the anode tapping point and earth is sufficiently large, the momentary anode voltage will be very high at the instant the aerial current is at maximum amplitude, and the anode current through the valve will be reduced to zero. Any increase in inductance beyond this point would tend to oppose the anode current and so oppose the oscillations.

If the inductance is sufficiently low, at the instant of zero aerial current the anode voltage will be so low that the anode current will reach saturation value. Consequently any decrease in the value of the inductance would oppose the decrease in the amplitude of the anode current on reaching the saturation value, and so oppose the oscillations. Thus there is evidently a position of anode tapping point between these two values which is the best for maintaining the oscillations and supplying maximum power to the aerial circuit with minimum dissipation in the valve.

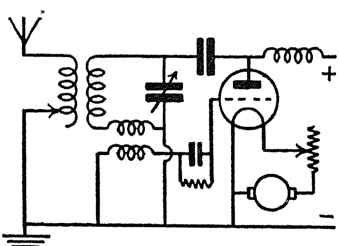


Fig. 128.

111. Coupled Circuit Arrangement.—In most cases the aerial circuit is connected direct to the valve circuit, as shown in Fig. 127, as the introduction of a coupled circuit, as shown in Fig. 128, is not usually necessary.

For long waves where any small variation in the capacity of the aerial, due to any movement in a wind, for example, does not seriously affect the frequency of the waves transmitted, a coupled circuit is not usually employed, as its introduction means additional losses. For short waves, however, a coupled circuit is sometimes employed to prevent any variation in the wave-length, even if the capacity of the aerial alters slightly.

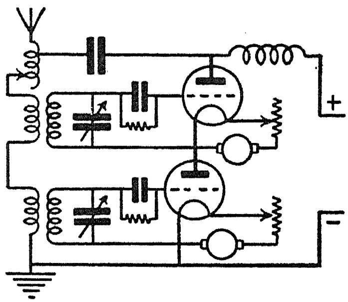


Fig. 129.

112. Valves in Series and Parallel. — In high power sets where it is necessary to use several valves to obtain the required power, the valves may be connected in series, or parallel, or in series-parallel.

Valves are connected in series where the voltage of the anode supply is too great for one valve, but where the current output of each valve is sufficient (Fig. 129). The usual arrangement, however, is to connect the valves in parallel, as shown in Fig. 130, since the difficulty is to get

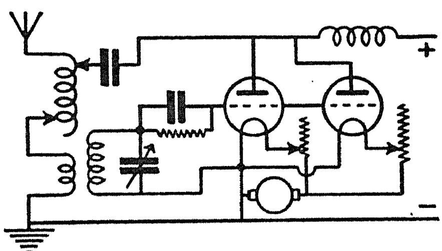


Fig. 130.

valves of sufficient current output. Very often separate grid leaks and condensers are used for each valve, in which case they are connected as shown in Fig. 131. Where still

greater power is required, valves are connected in both series and parallel.

One of the great difficulties experienced with multi-valve transmitting sets is that of ensuring that the load is shared equally by all the valves. It is essential that a separate control of the filament current of each valve should be adopted, although a common filament supply can be used.

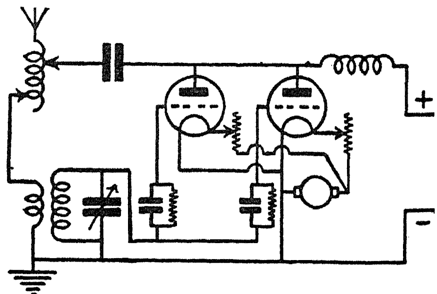


Fig. 131.

113. Anode Supply.—For very low power sets suitable for ranges of a few miles, the voltage of the anode supply may be of the order of a hundred volts. Where ranges of hundreds or thousands of miles are required, it is necessary to increase the voltage to thousands or tens of thousands to obtain the energy required in the aerial.

It should be noted that the oscillatory power produced in the aerial is obtained from the anode supply. The power required for heating the filaments of the valves is comparatively small, and even this would not be required if some form of filament could be constructed that would readily emit electrons at a normal temperature when placed in a strong electric field.

It will be seen, therefore, that the power supply to the anode must be at a high voltage, and must be greater than the power required in the aerial to allow for losses in the transmitting circuit.

The difficulty of designing suitable high voltage, direct current generators for large outputs has made the use of rectified alternating current the most common method of

supplying power to valve transmitting sets. In stations already fitted with spark sets, it has been possible to use the power supply already installed for these sets as the supply to the valve transmitting sets which have been installed to replace them.

A rectified alternating current supply to the anode also has the advantage of enabling interrupted continuous waves, or tonic train, to be transmitted by cutting out the smoothing condenser and applying the rectified voltage direct to the anode.

Two-electrode valves are very suitable for rectifying high voltage alternating current, and they are largely used as rectifiers in valve transmitting sets. Where single phase alternating current is used, the arrangement adopted is shown in Fig. 132. The supply from the alternator is stepped up to a suitable voltage by means of a transformer connected as shown. The current can only flow through the rectifying valves from anode to filament, and, in consequence, current flows through one valve only during one half cycle, and through the other valve only during the next half cycle. The current flowing along the two leads shown connected to the smoothing condenser is, therefore, unidirectional, but of varying amplitude. The variations in amplitude are practically smoothed out by the condenser, and the supply to the anode of the transmitting valve is practically steady.

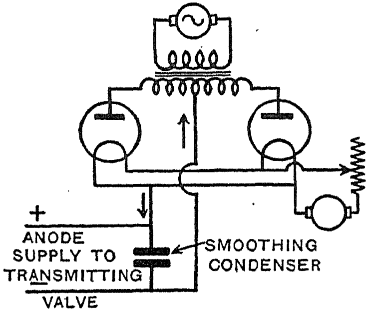


Fig. 132.

On cutting out the smoothing condenser, the anode voltage will vary in amplitude at twice the frequency of the alternator supply, and, therefore, the amplitude of the waves transmitted will vary correspondingly, thus producing I.C.W. (Interrupted continuous waves).

By cutting out one of the rectifying valves power will be supplied to the transmitting valve during one half cycle

only, the result being the transmission of I.C.W. whose train frequency is equal to that of the alternator frequency. The frequency of the note produced at the receiving station will, therefore, be half that of the note produced when both valves are used. The same result can be achieved by cutting out the rectifier altogether. Oscillations are then only produced during the half cycle when the anode is positive to the filament.

The main disadvantage of ordinary thermionic valves for use as rectifiers is their inefficiency owing to the energy required for heating the filaments. In some cases, therefore, neon or other gas-filled tubes are used with two anodes, *e.g.* in the $\frac{1}{2}$ kW and 1 kW Post Office sets. The life of these gas-filled rectifying valves is, however, less than that of an exhausted valve. Mercury vapour arc rectifiers are also being used in the Post Office 6 kW and 12 kW sets. They are not so steady as thermionic valves, but they have a much longer life and are more efficient.

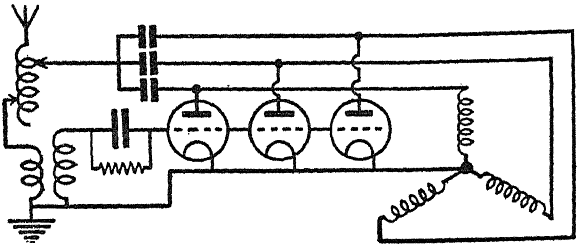


Fig. 133.

Methods of using polyphase currents for the power supply to transmitting valves are being developed. Some of these rectify the supply from each phase before applying it to the anodes of the transmitting valves, whilst others feed the anode of one valve from each phase direct, thus producing interrupted continuous waves which are more nearly pure continuous waves the greater the frequency of the supply and the greater the number of phases.

Fig. 133 shows one method of applying three phase current straight to a set composed of three transmitting valves. The frequency of the note produced at the receiving station will

be three times the alternator frequency. The disadvantage of first rectifying the multiphase supply is the number of rectifying valves required, or the number of anodes required if one rectifying valve only is used.

High voltage direct current machines are used in some cases, especially for low power sets, where alternating current is not available. The choice of the method to be employed depends on several factors, the chief of which is usually expense. From the point of view of the production of continuous waves free from harmonics a direct current supply is perhaps preferable, but usually the expense is greater than for alternative methods unless a high tension D.C. supply is already available. Examples of D.C. supply are the installations at Clifden and Carnarvon, where the machines were originally installed for spark apparatus and are now being used for the anode supply to valve sets.

For portable low power sets an induction coil is often used for the anode supply where it is desired to produce I.C.W. In order to produce a musical note of a suitable frequency at the receiving station a rotary make and break is found to be preferable to the ordinary make and break of the reed type.

An interesting account of various methods of supplying the anodes and filaments of transmitting valves is given in a paper read before the Institution of Electrical Engineers by Major Whittaker-Swinton.*

114. Filament Supply.—In low power sets the filament of the transmitting valve is usually supplied from a battery of accumulators or a small direct current generator. In sets of higher power it is usually found more convenient to use alternating current if an alternating current supply is used for the anode. As the function of the filament supply is simply to heat the filament to increase the emission of electrons, either direct or alternating current can be used, provided that in the latter case the frequency is sufficiently high to prevent the amplitude of the transmitted waves varying correspondingly and thus producing I.C.W. when C.W. is required. Frequencies not less than 200 are found to be satisfactory.

* *Journal I.E.E.*, Vol. 60, No. 311, July 1922.

The method usually adopted for high power sets is to feed the filaments of both the transmitting and rectifying valves from step down transformers which are supplied from the alternator used for the anode supply.

As the filaments of the rectifying valves are at a very high potential a specially insulated transformer is necessary for supplying these filaments, so it is usually kept separate from the transformer supplying the filament of the transmitting valve. In some cases, however, the same transformer is used with two secondary windings, the one for the rectifier filaments being highly insulated from the rest of the transformer. Fig. 134 shows a typical arrangement with separate transformers.

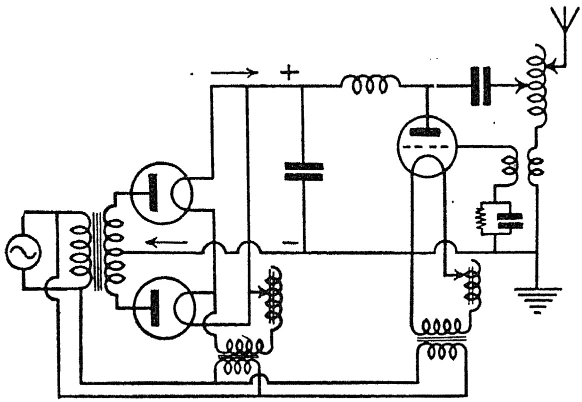


Fig. 134.

It has been found possible to utilise two-phase or three-phase currents for heating the filaments of multi-valve sets, even when the frequency is as low as 50 cycles per second. One method is to employ the same number or a multiple of the same number of transmitting valves as the number of phases used. Each filament is then fed from one phase, and although the emission in each valve fluctuates at the frequency of the supply, the resultant oscillations in the aerial are practically continuous. The same result has been obtained by providing more than one filament in each valve.

115. Methods of Signalling.—Quite a number of methods for using a valve transmitting set for the transmission of signals are possible, but in actual practice three only are used to any great extent. These are

(*a*) Signalling key in anode circuit.
(*b*) ,, ,, ,, primary supply circuit,
(*c*) ,, ,, ,, grid circuit.

In sets of low power a hand operated key can be inserted direct in the anode circuit, and signalling carried out by making and breaking this circuit. Where the anode supply is at a high voltage an electro-magnetically operated key can be used in the anode circuit so that the hand key can be insulated from the H.T. supply.

If the anode is supplied from a transformer, the current to be broken if the key is put in the H.T. side of the transformer, (*i.e.* direct in the anode circuit), is smaller than that required to be broken if the key were in the primary side. In the latter case, however, the hand key can be placed direct in the circuit provided the current is not too large. It may be noted in passing that in very high power sets it is necessary to have special keys, operated from a distance, whether they are placed in the primary or secondary side of the transformer. For such high power sets it is also necessary to blow air on to the switch contacts to prevent arcing.

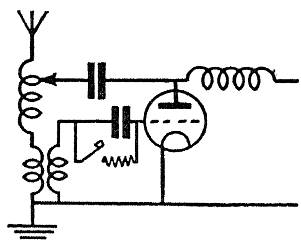


Fig. 135.

Signalling by means of a key in the grid circuit is becoming very popular on account of the small currents and low voltages to be controlled. The key is usually inserted in series with the grid leak as shown in Fig. 135. When the key is broken the negative charge produced on the grid cannot leak away and oscillations therefore cease. Energy is still being dissipated in the valve, however, by the steady anode current, as well as by the filament current, whereas with anode signalling the only energy dissipated when the key is not pressed is that due to the heating of the filaments.

For all but sets of low powers it is often found necessary to break both anode and grid circuits simultaneously, especially if reception is being carried out on the same aerial. If the grid circuit is tuned to the wave-length to be received energy is wasted through oscillations being set up in the grid circuit.

It is often found necessary in the case of high power sets to arrange for the set to oscillate slightly during spacing in order that oscillations may start readily and produce a good note. If a closed circuit is used this is not often necessary.

116. Production of Tonic Train or I.C.W.—It has been shown earlier in this chapter how interrupted continuous waves can be produced by using an alternating or rectified current supply to the anode. It is not necessary, however, to have an alternating current supply in order to be able to produce I.C.W. By using one valve to produce oscillations of an audible frequency these oscillations can be superimposed on the oscillations produced by the main transmitting valve, thus producing interrupted continuous waves or tonic train. This is the principle used in wireless telephony.

In both methods the signals heard at the receiving station without using heterodyne reception are produced by the oscillations superimposed on the main oscillations by auxiliary apparatus; in the case of wireless telephony these superimposed oscillations are produced by amplifying the oscillations produced in a microphone circuit by speech or music.

CHAPTER VIII.

WIRELESS TELEPHONY.

117. Introductory.—It is only within the last few years that the average person has heard much about wireless telephony, whereas wireless telegraphy has been accepted as one of the accomplishments of mankind for a much longer period. Wireless telephony has been an accomplished fact, however, for almost as long a period as wireless telegraphy, but its range of communication has not increased so rapidly as that of wireless telegraphy, owing to additional difficulties to be overcome and the greater demand for wireless telegraphy for signalling purposes.

As early as 1900 Fessenden succeeded in transmitting speech of a poor quality over a distance of a mile, using spark transmission, and by 1912 spark transmitting stations had succeeded in transmitting telephony over distances of several hundred miles, and quite a number of land and ship stations were working regularly by 1913.

Poulsen succeeded in establishing communication by wireless telephony over a distance of 600 feet as early as 1906, using an arc set with aerials only 15 feet high. In 1907 this range was increased to 170 miles, using an aerial 200 feet high and an input to the arc of less than 1 kW. Music transmitted by the same apparatus was heard 300 miles away. About the same time other experimenters using arcs obtained similar results.

When one remembers that these results were achieved before the days of amplifiers, and that the energy utilised at the transmitting station in many cases was not more than a kilowatt, it is realised that, although wireless telephony has only recently become a part of everyday life, it is not quite as recent an accomplishment as one is inclined to think.

As a means of communication for most commercial pur-

poses, wireless telegraphy is found to be preferable to wireless telephony on account of the greater speed possible with greater accuracy, just as line telegraphy is preferable to line telephony for the same reason. Under conditions where line telephony would be preferable to line telegraphy if either could be fitted, *e.g.* where two passengers in different aeroplanes desire to carry on a conversation with each other, wireless telephony is similiarly preferable to wireless telegraphy.

The most natural use of wireless telephony is, therefore, in cases where line telephony would be used if it were possible, but where the use of the latter is either impossible or difficult, such as between two moving positions or two positions intercepted by a long stretch of sea or rough country. The difficulty of preventing interference, and the cost of installation and maintenance of wireless telephony apparatus make it unlikely that line telephony systems over short distances will be replaced by wireless telephony, except in special cases, *e.g.* military purposes. For greater distances, however, the cost and upkeep of the lines necessary for line telephony may exceed the cost and upkeep of wireless telephony apparatus, and result in the advantage being with the latter system of communication.

As a means of enabling millions of people to listen to the speech of a great public man, or the singing of a famous opera star, wireless telephony has, of course, found a use of the greatest importance, in which it is not likely to fear any rival, unless some sensational discovery is made in connection with something as yet unknown to the scientist.

118. Sound Waves.—Before considering methods of communication by means of wireless telephony, it is necessary to consider the nature of the sounds it is desired to transmit. It is assumed that the reader has some knowledge of the theory of sound, so the subject will be dealt with only briefly here.

The average human ear is capable of detecting sounds of frequencies from about 12 periods per second to 30,000 periods per second. These values, of course, vary with different people. Sounds of higher or lower frequencies which may happen to be transmitted by wireless telephony will, therefore, not be audible.

Practically all sounds are complex, *i.e.* they are composed of sounds of different frequencies. A musical note is composed of a predominating sound of a certain frequency which determines the pitch, and in addition there are present sounds of smaller amplitude whose frequencies are usually multiples of the main or fundamental frequency. These overtones, as they are called, determine the quality of the note, and distinguish a note produced by one instrument or voice from a note of the same pitch produced by another instrument or voice. Sounds produced by speech are more complicated still, and each vowel or consonant is distinguished from the others by means of the relative amplitudes and frequencies of its component sounds.

It will be seen, therefore, that in order to reproduce speech or music or other sounds faithfully it is necessary to reproduce all the component sounds in exactly the same proportions as they were present in the original sound. If any unequal reproduction takes place distortion occurs. The prevention of distortion is one of the most difficult problems met with in wireless telephony, and special precautions have to be taken at both the transmitting and receiving stations.

119. Action of Sound on a Microphone.—As in line telephony, some kind of apparatus is necessary to transform energy in the form of sound into electrical energy before wireless telephony is possible.

The ordinary carbon microphone used in line telephony can also be used for wireless telephony to produce variations in an electric current corresponding to the sound vibrations. A certain amount of distortion occurs when using a carbon microphone, as all users of line telephones know. This is largely due to the response of the diaphragm being greatest to sounds of a frequency corresponding to its own natural frequency of vibration. For the transmission of speech this is not of vital importance, but for the transmission of music, where the range of frequencies is much greater, and where a small amount of distortion spoils the nature of the music, an aperiodic microphone becomes very desirable.

The design of a suitable microphone is, therefore, an important matter, and various types of microphones are used in addition to the carbon microphone. As the principle is

the same in all cases, viz. the production of variations in a current of electricity to correspond with the sound vibrations, the exact nature of the microphones used does not matter at this stage.

120. Modulation.—The action of the microphone is to vary, or **modulate** the steady electric current flowing through it to correspond with the sound vibrations picked up by the microphone. The next stage in wireless telephony, therefore, is to produce corresponding variations in the electric oscillations set up in the aerial, and so to transmit electromagnetic waves which are similarly modulated, either in amplitude or frequency. The usual method is to modulate principally the amplitude of the oscillations, and not the frequency, as the former method is much the simpler. In most methods, however, there is a certain amount of frequency modulation in addition.

It will be seen, therefore, that it is necessary to produce high frequency oscillations in the aerial by means of an ordinary transmitting set as used for wireless telegraphy, and then to modulate the amplitude of these oscillations by some means.

It is impracticable to produce electric oscillations of frequencies corresponding to the frequencies of the sound waves, as the wave-lengths would be enormous and the tuning of the circuits would have to vary at a rapid rate. For instance, if the frequency of the sound vibration were 1,000 cycles per second, the corresponding wave-length of the electromagnetic wave would be 186 miles, or 300,000 metres, and a huge aerial would be required for effective radiation at this wave-length.

121. Carrier Wave.—The steady oscillations required in the aerial for wireless telephony transmission (which are analogous to the steady current flowing in the microphone circuit) produce an electromagnetic wave of constant frequency which is radiated all the time wireless telephony is being transmitted. This wave is called the **carrier wave.**

It is evident that the carrier wave must be of such a nature that it has no audible effect on the receiving apparatus, otherwise a continuous note would be produced

in the telephones, or other apparatus used. If a damped wave, as produced by a spark set, is used, the frequency of the spark must, therefore, be above the limit of audibility.

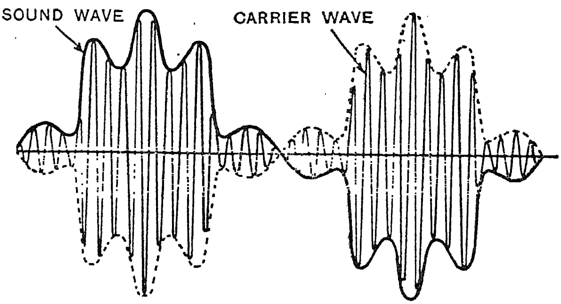


Fig. 136.

In addition, this high rate of sparking produces trains of electromagnetic waves which follow each other immediately, and so leave no dead space. The damping has, therefore, very little effect on the modulation, but it has sufficient effect to produce hissing sounds in the telephones. Spark methods of wireless telephony are, therefore, not often used nowadays for this reason, especially as other methods are simpler and more satisfactory.

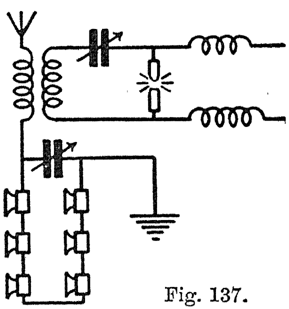


Fig. 137.

Clearly then continuous waves are most suitable for carrier waves, and wireless telephony is now practically always carried out by this means. Fig. 136 illustrates the nature of a sound wave, and its effect on the carrier wave.

122. Arc Methods of Transmitting Wireless Telephony.—The Poulsen arc was the first means of producing a continuous carrier wave for wireless telephony, but it has

now been superseded almost entirely by thermionic valve methods.

In 1907 Poulsen used the arrangement shown in Fig. 137 for transmitting wireless telephony. Six microphones in series were used and across them was connected a variable condenser, thus making the transmission partly one by change in wave-length.

Fig. 138 shows an arrangement used at one time by the Telefunken Company, but this has been superseded by their high frequency alternator and frequency changing transformer method. The microphone in this case decreases the coupling and the wave-length, and also decreases the aerial current by dissipating part of the oscillatory energy.

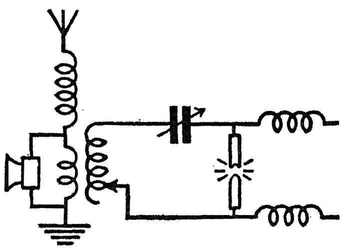


Fig. 138.

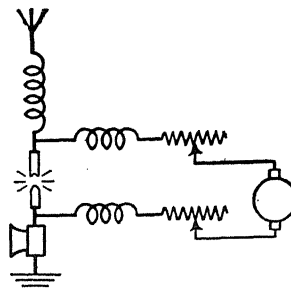


Fig. 139.

Similar circuits to those shown in Figs. 137 and 138 have also been used with a spark gap instead of an arc.

A typical arrangement with the arc in the aerial circuit is shown in Fig. 139.

123. High Frequency Alternator used for Wireless Telephony.—The Telefunken Company have adapted the high frequency alternator with frequency changing transformers for the transmission of wireless telephony.

The principle of the method consists in varying the magnetising ampere-turns of a transformer by the microphone current. In the arrangement shown in Fig. 140 the high frequency current from the alternator or frequency changing transformers flows through the tuned circuit

formed by the condenser and the primary of a transformer. The secondary of the transformer is in the aerial circuit. The microphone current varies the inductance of both these circuits and so modulates the aerial current. A special arrangement of microphones in parallel is used to give the necessary current for effective speech control. Iron-cored chokes are placed in the microphone circuit to prevent the passage of H.F. oscillations.

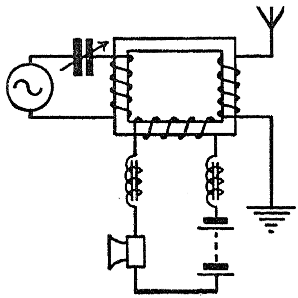


Fig. 140.

In practice the Telefunken Company use the microphone current to supply magnetising windings on the frequency changing transformer, and thus vary the magnetising effect produced by the steady magnetising current flowing through separate windings. It is found that hysteresis effects are not appreciable.

A method based on the same principle of magnetic control, or **ferro-magnetic control** as it is often referred to, is used

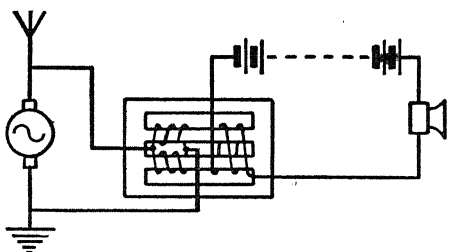


Fig. 141.

by the General Electric Company of America. In this system a magnetic amplifier is used to apply a variable inductance, produced by the microphone, across the terminals of an Alexanderson high frequency alternator (Fig. 141). The winding in series with the microphone causes variation in the inductance of the two parallel windings connected across

the alternator and so produces modulated oscillations in the aerial. The single winding of the magnetic amplifier is wound over the cores of both the parallel windings to prevent high frequency induction in the former from the latter. In practice several modifications are introduced for satisfactory working but the principle remains the same.

124. Thermionic Valve Methods.—By far the most important method of transmitting wireless telephony is by means of the thermionic valve. As valve transmitting sets for wireless telegraphy are tending to replace other systems to a very large extent it is a fairly simple matter to utilise the same set for either wireless telegraphy or wireless telephony. Where a set is required solely for wireless telephony a valve set is employed in practically all cases.

The following are the chief methods of modulating the high frequency output of an oscillating valve :—

(*a*) Modulation of the resistance of the aerial.
(*b*) Modulation of the grid voltage of the valve.
(*c*) Modulation of the anode voltage of the valve.

125. Modulation of Aerial Resistance.—The modulation of the resistance of the aerial involves connecting the microphone either directly in the aerial circuit or in an inductively coupled circuit. Fig. 142 shows the microphone placed directly in the aerial circuit. An arrangement with the microphone connected inductively to the aerial circuit is shown in Fig. 143. In this case a variable condenser is connected in the microphone circuit to enable the circuit to be tuned sufficiently near the frequency of the aerial circuit to enable the necessary amount of energy to be absorbed to produce modulation of the aerial current.

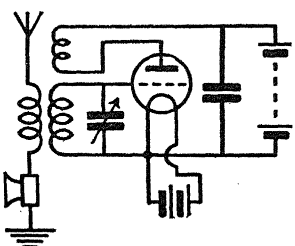


Fig. 142.

In both these arrangements modulation of the aerial current is carried out by the variations in the microphone resistance, and high frequency current flows through the

microphone. These methods are not so effective as those employing modulation of grid or anode voltages, as in the last two cases heavy currents do not pass through the microphone, and if necessary the microphone may be some distance from the transmitting set.

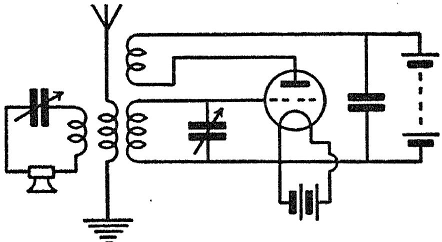


Fig. 143.

126. Modulation of Grid Voltage.—A typical circuit employing grid modulation is shown in Fig. 144. The microphone is shown coupled to the grid circuit by means of an iron-cored transformer. The fluctuations in current in the microphone circuit cause corresponding fluctuations in

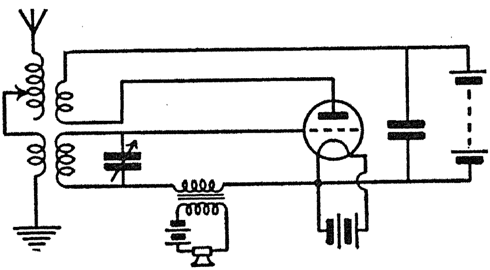


Fig. 144.

the potential of the grid and so modulate the amplitude of the generated oscillations. This method is often used in small sets, but in larger sets modulation of the anode voltage is found to be more satisfactory.

127. Modulation of Anode Voltage.—Wireless telephony transmitting sets employing modulation of the anode voltage are the most common kind met with in practice. They are largely used in aircraft and for broadcasting purposes.

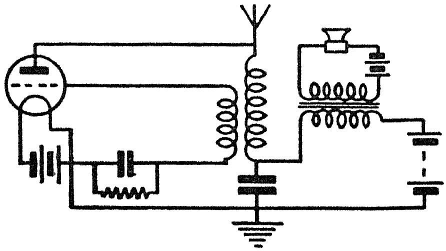


Fig. 145.

Fig. 145 shows a simple circuit employing this form of modulation. The circuit shown is an ordinary valve transmitting circuit connected directly to the aerial, the anode supply flowing through the aerial inductance. The microphone is coupled inductively to the anode supply circuit by means of a step up transformer. Variations in the microphone current therefore produce variations in the anode voltage and so modulate the aerial oscillations.

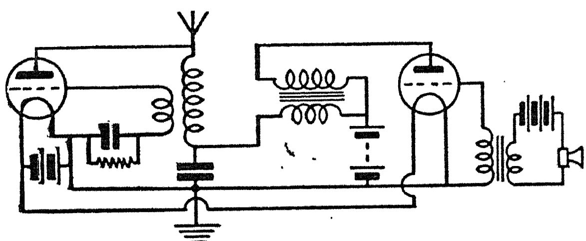


Fig. 146.

In practice it is found necessary to amplify the microphone potentials before applying them to the anode supply circuit. A low frequency amplifying valve is therefore included in

the circuit as shown in Fig. 146. If necessary additional low frequency valves can be added, and for large sets this is usually done. Fig. 146 shows common batteries used for both the oscillating valve and the control valve, as it is called. It has been found unnecessary to use a transformer for coupling the low frequency potentials to the anode circuit of the transmitting valve, as a choke coil is found to be simpler and more effective.

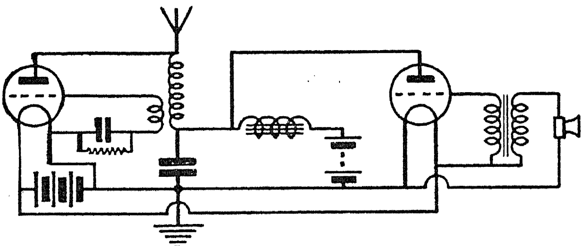


Fig. 147.

Fig. 147 shows such a circuit as used on aeroplanes. The steady current for the microphone is supplied from the common filament battery. This system is very suitable in cases where the microphone is situated away from the rest of the set, and this has been found a great advantage in aeroplanes, and of course in many other cases. An interesting account of the development of this system for use in aeroplanes is given in a paper by Major Prince.*

128. Duplex Wireless Telephony.—In order that wireless telephony may be as convenient to use as line telephony, it is necessary that a person speaking into a microphone may also hear an interruption from the person he is addressing, *i.e.* at any station it must be possible to transmit and receive at the same time.

The simplest form of wireless telephony for two way working utilises a hand operated switch which cuts out the

* "Wireless Telephony in Aeroplanes" by Major C. E. Prince, *Journal I.E.E.*, Vol. 58, No. 291, p. 377, May 1920.

receiving apparatus when transmitting to prevent damage being caused to it by the relatively high power oscillations transmitted. This method does not permit of simultaneous transmission and reception, called **duplex** telephony. It is necessary, therefore, to adopt some other means of protecting the receiving gear if true duplex working is to be possible.

A method used for ground stations where space is available employs two separate aerials, one for transmitting and one for receiving, and uses slightly different wave-lengths. The transmitting and receiving aerials at one station are placed sufficiently far apart to prevent interference, as the difference in wave-length used is only small owing to the necessity for keeping the band of wave-lengths small for any particular purpose to prevent interference with other stations.

This method is suitable for places where it is possible to erect two aerials at the required distance apart, but it is not suitable for ship and aircraft working. It is necessary, therefore, to employ a system requiring only one aerial if duplex telephony is to be possible in the case of ships and aircraft and similar cases. Several systems have been suggested, but so far no really satisfactory method has been developed sufficiently for general adoption.

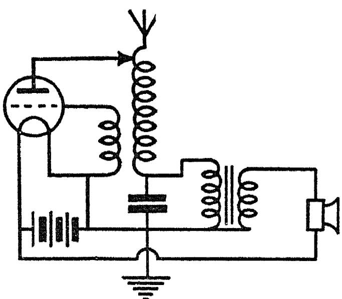


Fig. 148.

One method, which is only a partial solution, uses an arrangement whereby the act of speaking into the microphone starts the oscillations, which stop when speech stops. This arrangement is often referred to as the **quiescent aerial** method. In this method the anode supply to the transmitting valve is produced solely by the microphone, there being no anode supply proper. Fig. 148 illustrates the principle of the method. In practice it is found necessary to amplify the microphone potentials as shown in Fig. 149.

The quiescent aerial system is not satisfactory as developed at present, as the quality of speech transmitted is poor, owing

to the inertia effect of the circuit. If small oscillations are maintained permanently to overcome the time lag, it is found that poor reception occurs.

Other methods have been tried using rejector circuits, and using separate wave-lengths for transmission and reception. The earth lead in these cases is in two parts, one carrying the transmitting current and the other the received current, the receiving apparatus being connected to the latter circuit.*

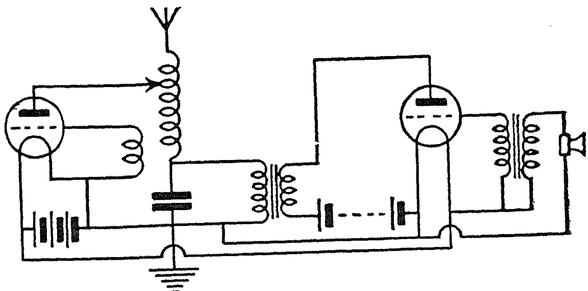


Fig. 149.

129. Reception of Wireless Telephony.—Receiving apparatus used for wireless telegraphy can be employed for the reception of wireless telephony employing the same wave-length. In the case of telegraphy, however, a certain amount of distortion does not matter, but for telephony any distortion destroys the quality of the speech or music. It is essential, therefore, that the amplifying valves used in the receiving set should have as straight a portion as possible in the middle of the characteristic curve, otherwise unequal amplification of the various components of the oscillations corresponding to the components of the sound transmitted will occur.

In addition care must be taken to make the tuning of all the circuits used in the set as flat as possible over the range covered by sound frequencies. For this reason it is often found better to use resistance coupled low frequency amplifiers

* For further information see Capt. P. P. Eckersley—"Duplex Wireless Telephony: Some Experiments on its Application to Aircraft." *Journal I.E.E.*, Vol. 58, No. 293, p. 555, July 1923.

instead of transformer coupled low frequency amplifiers. The use of too much reaction also causes distortion.

Where extremely loud signals are required, such as when a loud speaker is employed, several stages of low frequency amplification are required, and any distortion that may have occurred before the signals are rectified is amplified correspondingly, apart from any additional distortion that may occur owing to the additional low frequency valves.

The telephones or loud speaker also are responsible for a certain amount of distortion, especially in the case of the loud speaker. It is extremely difficult to make a truly aperiodic telephone or loud speaker, especially for loud signals, and resonance effects occur therefore. This problem is receiving careful investigation and aperiodic loud speakers, possibly not very efficient, are promised in the near future,

130. Elimination of the Carrier Wave.—Although a carrier wave is usually employed for the transmission of wireless telephony it is not theoretically essential, and experiments are being carried out to enable the carrier wave to be eliminated in order to reduce the power required for transmission and to prevent interference.*

It is shown in Chapter I. (see also Chap. XIII.) that when two oscillations of different frequencies are superimposed on each other the resultant oscillation has two components, the frequency of one being equal to the sum of the two frequencies, and the frequency of the other being equal to the difference. Thus if p is the frequency of the carrier wave and q is the frequency of the oscillations produced by a sound vibration, the resultant waves transmitted will be composed of one whose frequency is $p + q$ and one of frequency $p - q$. If the sound vibration is complex q will vary for the different frequencies composing the complex sound.

It will be seen, therefore, that the sound is actually transmitted by waves of frequencies extending above and below that of the carrier wave, and that the actual carrier wave need not be transmitted once these side waves have been produced in the transmitting circuit.

* See Dr. H. W. Nichols—"Transoceanic Wireless Telephony." *Journal I.E.E.*, Vol. 61, p. 812, July 1923.

Fig. 150 illustrates the resultant amplitude of the carrier wave produced by the superposition of the low frequency oscillations due to the sound. The amplitude of the oscillation is measured from the zero line, and the successive values of the amplitude of the oscillation must be in exactly the same proportion at the receiving station as at the transmitting station if faithful reproduction is to be obtained.

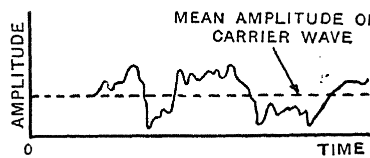


Fig. 150.

If the carrier wave is removed before the wave is transmitted the dotted line representing the mean amplitude of the carrier wave will become the new zero line, and the amplitudes of successive oscillations will not have the same ratio as they had originally. It will be necessary, therefore, to add the carrier wave at the receiving station to bring the zero line to the correct position, and so reproduce the original conditions.

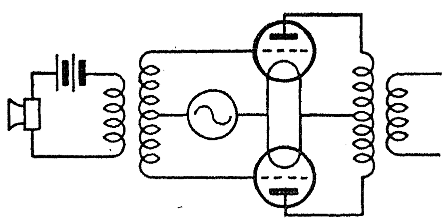


Fig. 151.

One method of eliminating the carrier wave is illustrated in Fig. 151. Before microphone currents are applied to the input transformer the carrier wave generated by the small alternator produces no effect in the output side of the output transformer if the two halves of the intermediate circuit are symmetrical. When microphone currents are applied, however, there is a corresponding output and no carrier wave will be present. There will be waves present of frequencies covered by the two side bands, and as these are wireless fre-

quencies transmission is possible. For speech these side bands will each cover a period of about 3,000 cycles per second, and the frequencies of the oscillations will therefore extend to 3,000 above and below that of the carrier wave.

The amplitude of any component oscillation of frequency $p + q$ is equal to the amplitude of the corresponding component oscillation $p - q$, hence each side band contains all the elements of the signal and it is not essential to transmit both side bands. Special filter circuits can be used to eliminate one side band; this decreases the risk of causing interference with other stations owing to the wide range of component frequencies of waves transmitting telephony, and also decreases the power required. When the oscillations corresponding to one side band have been produced, they are amplified sufficiently to produce the necessary power in the aerial, which will be less than that required to transmit the complete modulated carrier wave.

This system is being tried for trans-oceanic work especially on account of its reduced interference with wireless telegraphy work. A similar system for line telephony is in use in the United States on carrier telephone circuits.

131. Microphones.—The carbon microphone transmitter employed in line telephony has been used to a large extent for wireless telephony. The difficulties experienced in the early days of wireless telephony, when the microphone was required to control fairly large currents which caused packing and burning of the carbon granules, are not experienced with modern valve transmitting sets and amplifiers of the small modulated current. The carbon microphone used for ordinary telephony, however, produces a certain amount of distortion due to its natural resonant frequency and to the non-linear variation of resistance with pressure. It is therefore not entirely satisfactory for the transmission of music.

Several modifications have been introduced to reduce the distortion produced by a carbon microphone. The diaphragm is constructed to have a high natural frequency with high damping, and in the "push-pull" type the diaphragm operates on two carbon buttons, one on each side, connected in such a manner that the distortion produced by the non-linear variation of resistance is eliminated.

The condenser microphone is now used to a large extent as, it produces practically no distortion. In this type a heavily damped, light, tightly stretched diaphragm forms a small condenser whose capacity varies with the air pressure. A steady voltage is applied to the microphone through a resistance across which an amplifier is connected. The variations in P.D. across the resistance are then proportional to the sounds which cause variations in the capacity of the condenser. The natural frequency of this form of microphone is about 16,000 periods per second.

Several other forms of microphone are in use, one of which is the electromagnetic type. In this case a light coil is suspended in a magnetic field and is damped both mechanically and electrically. Sound waves cause the coil to vibrate and so produce corresponding E.M.F.'s in the coil.

Other types are used which depend on the direct action of sound waves on a silent glow discharge, or on the current flowing across an ionised air space between a Nernst glower and a cold electrode.

Various forms of liquid microphones have been devised, but they have had very little application and appear to be obsolete. They usually depended for their action on the effect of a diaphragm on a conducting liquid jet. Motion of the diaphragm altered the length and cross-section of the jet and so altered the resistance.

132. Loud Speaking Telephones.—An ordinary telephone earpiece can be attached to a horn to produce a simple form of loud speaker. The strength of signals, however, in the ordinary telephone cannot be increased beyond a certain point which is determined by the possible displacement of the diaphragm before it strikes the poles of the permanent electro-magnet. It is necessary therefore for a loud speaking telephone to differ somewhat from an ordinary telephone if a large volume of sound is required.

In a number of types of loud speakers the permanent magnet used in an ordinary telephone is replaced by an electro-magnet excited by a small battery. The output current from the receiving amplifier flows through a step down transformer, the secondary of which is connected to a movable coil placed in the field of the electro-magnet. Varia-

tions in the output current of the amplifier therefore cause corresponding variations in the position of the coil which is attached to a diaphragm (Fig. 152).

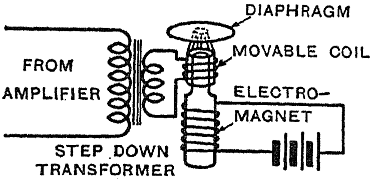


Fig. 152.

The design of an efficient, distortionless loud speaker is by no means simple, and the subject will not be dealt with here. The reader is referred to the reports of joint meetings of the Institution of Electrical Engineers and the Physical Society of London.*

* *Journal I.E.E.*, Vol. 62, p. 265, March 1924, and p. 373, April 1924.

CHAPTER IX.

DIRECTIONAL TRANSMISSION AND RECEPTION OF ELECTROMAGNETIC WAVES.

133. Uses of Directional Transmission and Reception of Electromagnetic Waves.—In very many cases a wireless telegraphy or wireless telephony station is intended to work only with one other station, and it is evidently a waste of power for energy to be radiated uniformly in all directions in such cases, and undesirable for the receiving aerial to be capable of receiving equally well in all directions on account of interference. The necessity for designing aerials to transmit or receive as nearly as possible in one direction only is therefore evident.

In addition to the case where communication is desired between two stations only, it is often desirable to have some means of locating the position of a wireless telegraphy or telephony station, and the development of methods to enable this to be done has made great progress during the last few years.

During the war it was of great importance to be able to locate an enemy wireless station, whether situated on the ground, on the sea, or in the air, and this problem received a great deal of attention. It was also very important that a ship or aeroplane should be able to determine its own position, and it was found possible to be able to do this by wireless direction-finding apparatus situated either on the moving station or on some fixed ground station. In the former case the ship or aeroplane was able to determine the direction of two or more wireless stations of known position, and was therefore able to locate its own position independently of anyone else. In the latter case the fixed

stations were able to obtain the direction of the moving wireless station relative to each of them, and so inform the moving station of its position.

In other cases some form of revolving wireless beam was sent out so that a ship or aeroplane not fitted with special apparatus could determine the bearing of the station by means of its ordinary wireless receiving apparatus.

The importance of wireless direction-finding for navigation purposes will be realised, and since the war the methods developed for war purposes have been applied to the mercantile marine and to civil aviation.

134. Directional Transmission of Electromagnetic Waves.—The necessity of being able to transmit electromagnetic waves as nearly as possible in one direction only was realised in the early days of wireless telegraphy. Hertz showed that electromagnetic waves behaved similarly to light waves, and he used reflectors at both the transmitting and receiving positions to concentrate the waves into a beam. Marconi employed reflectors in his earliest experiments, but later, when he discovered that longer waves gave an increased range, he discarded reflectors, as the size required for use with the longer waves was hardly practicable.

As the *first* application of wireless telegraphy was for communication with ships there was not much need for directional transmission, and little development on these lines took place for a long time, although Erskine-Murray in 1899 erected two vertical aerials with the transmitter connected between them in order to concentrate the radiation as much as possible in one direction. This was probably the first attempt at directional transmission of long waves, but the experiments were not continued. Now, however, that the ranges obtainable are as long as are required on the earth, attention is being devoted more and more to the reduction of the power required, and directional transmission is one of the solutions being attempted.

Reflectors necessitate the use of short waves, which have certain disadvantages for long distance working, but recent experiments with short waves have given remarkable results over fairly long ranges. Marconi has recently described

a method of producing a beam of short waves, by means of which communication is practicable over long distances with a much lower power than that required for ordinary methods.*

Directional transmission has been obtained usually by arranging the aerial or aerials in some special manner so that the currents in different parts of the aerial system are out of phase. The various methods in use are described on subsequent pages.

135. Marconi Bent Aerial.—A type of aerial that has been largely used by the Marconi Company is the long horizontal type fed at one end (see Chapter X.). Marconi determined the radiation curves of such an aerial about 1906, and found that the aerial was strongly directional for both transmitting and receiving (Fig. 153).

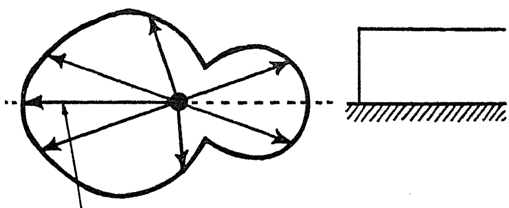


Fig. 153.

Various theories have been advanced to explain the directional effect of this type of aerial, the generally accepted one being based on the effect of the bad conductivity of the earth in the neighbourhood of the aerial.

136. Bellini-Tosi System.—Various systems for the directional transmission of electromagnetic waves have been tried using several aerials with their currents out of phase, but the one of most importance is the Bellini-Tosi system.

A system composed of two vertical wires, connected together at the foot through the transmitting inductances, as shown in Fig. 154, radiates equally well in either direction

* See *Electrician*, July 11th, 1924.

in the plane of the aerial, because the two aerial currents assist each other. In other directions, however, there is little radiation.

This arrangement can, therefore, be used for directive transmission in the direction of the plane of the aerial. By introducing a similar system at right angles to it radiation can be obtained in the plane of the new system as well if required. This is accomplished in the Bellini-Tosi system by a rotating primary coil which is common to the coupling coils of the two aerial systems. The two coupling coils are arranged at right angles, hence, by rotating the primary coil, energy may be transferred to either or both aerial systems in any proportion, and so maximum radiation obtained in any direction. The coupling transformer (see Fig. 155) is called **a goniometer.** Owing to the difficulty of fitting vertical aerials, sloping ones were generally used on ships, as shown in Fig. 156.

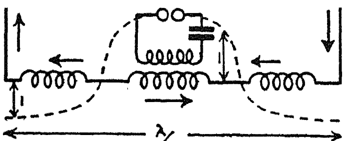


Fig. 154.

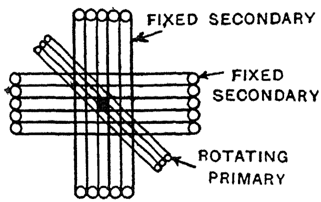


Fig. 155.

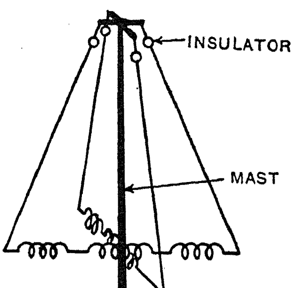


Fig. 156.

The Bellini-Tosi system radiates equally well forward and backward, so that energy is wasted in one direction. A centre vertical aerial carrying current 90° out of phase with the side aerials has been used by Bellini and Tosi to prevent this.

Although it has been used for directional transmission, the Bellini-Tosi system is best known on account of its

suitability for directional reception (see page 180). It is now usual to make each pair of vertical aerials into a closed loop for receiving purposes, a modification which was introduced by Prince in 1912. Closed loops are not very suitable for transmission purposes, as their radiation properties are very poor compared with those of open aerials.

137. Directional Transmission for Navigational Purposes.—Various methods are in use for radiating waves in a constantly changing direction for navigational purposes, in a similar manner to the revolving beam of a lighthouse.

A system which has been used to a fairly large extent is the Telefunken radial aerial arrangement. A large number of radial aerials of the Marconi bent aerial type are erected at equal angles round the transmitter. The rotating effect is obtained by transmitting on each aerial or pair of opposite aerials in turn.

A method developed by the Royal Air Force utilises two coils at right angles joined in series through a reversing switch, a tuning condenser, and a coupling coil (Fig. 157).* Power is supplied to the aerial system through the coupling coil. The aerial system is rotated at a uniform rate, in some cases one revolution every minute, and the reversing switch is operated continuously at two to four times a second. When either of the coils is pointing towards a receiving station successive signals are of equal intensity, in other positions they are not. The observer is thus able to tell when one of the two coils is pointing towards him. A special signal is sent out when the coils are in a predetermined direction so that the observer can determine the relative direction of the trans-

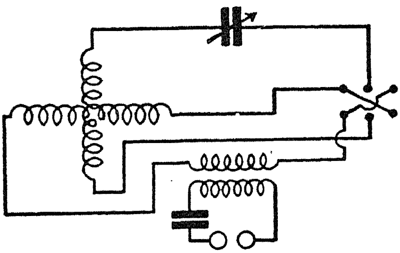


Fig. 157.

* See "Directional Transmission of Electromagnetic Waves for Navigational Purposes," by Major J. Erskine-Murray, D.Sc., and J. Robinson, Ph.D., *Journal I.E.E.*, Vol. 50, p. 352, March 1922.

mitting station. One of the frame coils is made larger than the other so that during a rotation of 180° there are two sets of successive signals of equal strength, one set being stronger than the other. Thus any confusion as to which coil is pointing towards the observer is prevented.

The above system does not rely on observation of signals of minimum or maximum intensity, which is necessary when a revolving Bellini-Tosi system of aerials or other revolving directional aerials are used.

Several stations employing a beam of very short waves have now been erected round the coast of Great Britain. These employ revolving parabolic reflectors, and are, therefore, only suitable for short waves of the order of several metres, which necessitate special short-wave receiving apparatus being installed on ships making use of these "wireless lighthouses." A distinctive signal is sent out every half or whole point of the compass, so that a ship can determine its bearing relative to the beacon station. This obviates the necessity for accurate timing of the interval between the time a signal is sent out, when the beam is in a predetermined direction, and the time the beam is pointing towards the ship.*

138. Directional Reception of Electromagnetic Waves.—The determination of the position of a wireless station for navigational purposes by methods involving directional reception of electromagnetic waves is much more common than such determination by methods involving directional transmission. Methods of the latter kind are comparable with position finding of a ship by means of a lighthouse, and methods of the former kind are comparable with the usual visual methods on board ship employing the sextant.

Directional reception has other functions which cannot be fulfilled by directional transmission, such as the location of enemy wireless stations, etc.

The importance of directional reception, as well as directional transmission, was realised in the early days of wireless

* See "Short-wave Directional Wireless Telegraphy," by C. S. Franklin, *Journal I.E.E.*, Vol. 60, p. 930, August 1922.

telegraphy—Hertz used reflectors for receiving as well as transmitting—but it was not until about the year 1910 that directional reception was used deliberately for determining the position of a wireless station, and until the requirements of the war caused the rapid development of direction-finding, it had very little application. The increased sensitivity of receiving apparatus has enabled direction-finding apparatus to be used satisfactorily under conditions of limited space, where the installation of suitable apparatus would otherwise have been impossible.

All direction-finding systems based on directional reception depend on the fact that a closed loop is acted on to a greater extent by electromagnetic waves arriving in a direction parallel to the plane of the coil than by waves arriving from any other direction. The original Bellini-Tosi system was essentially the same, except that the upper connection between the two sides of the loop was omitted.

When a receiving station is designed to work with a particular transmitting station, it is obviously an advantage to employ a receiving aerial which is directional. In such cases a loop aerial, a Marconi bent aerial, or the more recent Beverage horizontal wire aerial may be used (see page 183).

139. E.M.F. Induced in a Straight Wire and a Closed Loop.—Before considering the effect of an electromagnetic wave on a vertical wire or a closed loop, it is necessary to understand clearly the nature of an electromagnetic wave.

Returning to the case of the transmission line considered in Chapter II. it will be seen that the conditions present at any point in space through which electromagnetic waves are passing are equivalent to those produced by a high frequency oscillatory current flowing vertically through that point through an oscillatory circuit. The current is produced by an electric field in phase with the magnetic field produced by the current but at right angles to it in space.

Electro-motive forces produced in conductors by an electromagnetic wave can therefore be calculated in terms of either the electric field or the magnetic field, but the E.M.F.'s must not be calculated in terms of one and added indiscriminately to those calculated in terms of the other, under a mistaken idea that the resultant would be the actual resultant E.M.F.

produced. It must be borne in mind that the effect is that of an oscillatory electric field which produces an oscillatory current which produces an oscillatory magnetic field.

Now consider a vertical wire in the path of an electromagnetic wave travelling at right angles to it. The E.M.F. induced in it may be calculated as being due to either the electric field or the magnetic field of the wave, but not both.

If h = the length of the wire,

v = the velocity of the electromagnetic wave, *i.e.* the velocity of the magnetic field,

H = the strength of the magnetic field,

E_1 = the E.M.F. induced in the wire,

then $E_1 = hvH$ electromagnetic units.

If E = the strength of the electric field, then Eh is the E.M.F. in electrostatic units induced in the wire. Since the ratio of the electrostatic unit of E.M.F. to the electromagnetic unit of E.M.F. is equal to the velocity of light it is evident that $Eh = hvH$, *i.e.* the E.M.F. induced by the electromagnetic wave is the same whether calculated in terms of the electric field or the magnetic field.

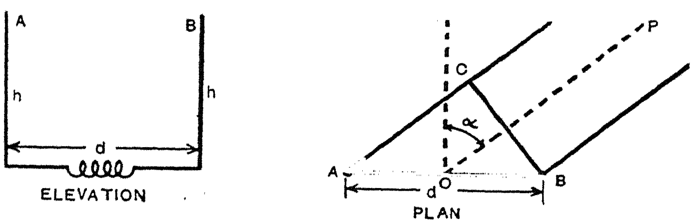


Fig. 158.

Now consider two vertical wires A and B separated by a distance d as shown in Fig. 158 and connected together through an inductance. The E.M.F.'s induced in the two wires at any instant by an electromagnetic wave will be slightly different depending on the direction of the wave. If the direction of the wave is indicated by PO the conditions at B and C will be equal at any instant, but those at A will

lag behind those at B and C depending on the distance CA. The E.M.F. across the inductance will be the difference between the E.M.F.'s induced in A and B and will therefore increase as AC increases, and will be a minimum when PO is at right angles to AB and a maximum when PO is in line with AB. The direction of an electromagnetic wave can be determined therefore by rotating an aerial system of this nature.

If d is small compared with the wave-length the resultant E.M.F. will be small, so it is obvious that the greatest resultant E.M.F.'s will be obtained for short waves with given values of d and h.

The polar diagram of reception of the system of aerials shown in Fig. 158 is shown in Fig. 159, where the strength of signals received in a direction making an angle α with the normal to the plane of the aerials is represented by the vector r.

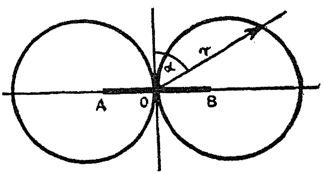


Fig. 159.

The wave-front has been assumed to be vertical when considering the E.M.F.'s produced, but in practice it is very often tilted forward owing to the resistance of the earth causing energy to be dissipated from the wave. There will then be both a vertical component of the electric field and a horizontal component, and a vertical component as well as a horizontal component of the magnetic field. E.M.F.'s will therefore be induced in the horizontal connection between the two aerials. If the upper ends are connected an E.M.F. will also be induced in this connection in opposition to the E.M.F. produced in the lower one, but will be slightly out of phase with it. It will be necessary therefore to take these E.M.F.'s into account in a complete calculation.

The E.M.F. induced in a loop will be due to the horizontal component only of the magnetic field, as the vertical component will not cut it. Hence it is quite a simple matter to calculate the E.M.F. in terms of the horizontal component of the magnetic field instead of in terms of the electric field.

If the maximum value of the horizontal component of the magnetic field is H_m and E_m is the maximum value of

the E.M.F. induced in the loop then, provided the sides of the loop are small compared with the wave-length,

$$E_m = \omega H_m A \cos \alpha,$$

where $\omega = 2\pi$ times the frequency of the wave, $A =$ the area of the loop, and $(90^\circ - \alpha) =$ the angle between the direction of the horizontal component of the magnetic field and the plane of the loop.

Evidently E_m will be zero when $\alpha = 90^\circ$, *i.e.* when the plane of the loop coincides with the vertical plane containing the resultant magnetic field of the wave-front, and the E.M.F. will be greatest when the plane of the loop lies in the direction in which the wave is travelling.

The E.M.F.'s induced by two waves travelling in opposite directions are obviously 180° out of phase, consequently if the phase of the E.M.F. produced by a wave can be determined no ambiguity arises as to the position of the transmitting station. Without such determination of "sense" it is only possible to say along which line the station lies and an error of 180° is therefore possible.

The reciprocal bearing can be eliminated by determining the phase of the induced E.M.F. with respect to the E.M.F. induced by the same wave in a vertical wire. In the latter case the E.M.F. has the same phase whatever the direction and so can be used as a standard. When the coil is in one direction the two E.M.F.'s will assist each other, and will oppose each other when the coil is moved through 180°. The correct bearing to take can therefore be determined by calibrating the apparatus by means of stations of known position.

140. Rotating Coil System.—A single closed loop of suitable size for easy rotation does not give sufficient E.M.F. for direction finding purposes as a general rule. It is usually necessary, therefore, to use a coil of several turns and to tune the coil to give resonance.

The coil may be of the box type where the turns are side by side, or of the pancake type where the turns are wound spirally in the same plane. In the former case the separate turns are not in separate planes owing to being wound on the "skew" and this may give the effect of an equivalent turn in the plane of the coil's axis. This produces a slight error

which is usually negligible or easily eliminated by adjusting the pointer.

The E.M.F. produced across the variable tuning condenser is detected by the usual method of detecting wireless signals, and it is usually necessary to employ an amplifier. The lack of sensitive detectors in the early days of wireless telegraphy prevented the general use of frame aerials.

The leads to the detector and the detector circuit itself should have negligible inductance compared with that of the coil, otherwise an incoming wave produces a constant E.M.F. in the circuit which will be independent of the position of the coil. If this is appreciable the position of minimum E.M.F. will be difficult to determine and the zero will be "blurred."

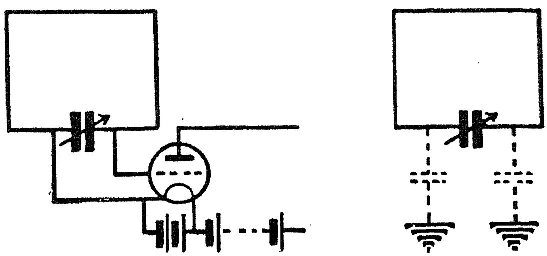


Fig. 160.

The capacity to earth of the detector circuit will cause the whole system to act as a vertical aerial, and capacity currents will flow to earth from the vertical sides of the coil independent of the direction of the coil (Fig. 160). As a rule the capacity to earth of the grid of the first valve will be much less than the capacity to earth of the filament to which the batteries, etc., are connected. The result will be that the capacity currents are unequal and produce a P.D. across the tuning condenser even when there is no E.M.F. in the coil itself. This is said to be due to the "**vertical**" or "**aerial**" effect of the coil, and produces ill-defined zeros.

One method of eliminating "vertical" is to introduce a compensating condenser between the grid of the first valve and earth in order to make the two capacity currents equal.

When determining the bearing of a station it is usual to find the position of the rotating coil for minimum strength of signals, as the rate of change of intensity round the minimum point is greater than that round the maximum as the intensity varies with the angle of rotation according to a sine law. This is usually effected by finding two positions, one on each side of the minimum, where the signals have equal strength; the minimum position is then midway between them.

A rotating single loop does not enable the side of the direction finder on which the transmitting station is situated to be determined; it merely gives the position of a line through the direction finding station and the transmitting station. The reciprocal bearing can be eliminated by comparing the phase of the E.M.F. induced with the E.M.F. induced in a vertical aerial. (See page 178). The aerial or vertical effect of the coil can be used for this purpose.

141. The Bellini-Tosi System used for Directional Reception.—The original Bellini-Tosi direction finder used open aerials instead of loops, but later it was found an advantage to join the upper ends to form closed loops.

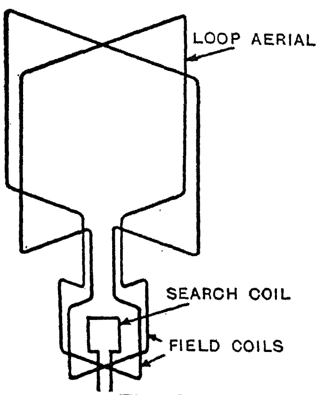


Fig. 161.

The Bellini-Tosi system as used at the present time uses two closed vertical loops either rectangular or triangular in shape, erected with their planes at right angles (Fig. 161). A small field coil is connected in series with each loop and these two field coils are also mounted at right angles. A small search coil is pivoted so that it can be rotated in the resultant field of the two field coils, and carries a pointer.

If the electrical constants of the two loops are identical, the magnetic field produced by one field coil will be proportional to the magnetic field cutting the corresponding loop, and the magnetic field produced by the other field coil will

be proportional to the magnetic field cutting its corresponding loop. The miniature fields are at right angles and so are the magnetic fields cutting the loops, and their resultant will correspond in magnitude and direction with the main field whose components induce E.M.F.'s in the loops. The search coil rotating in the miniature field is therefore equivalent to a rotating coil in the main field, and the direction of the waves can thus be determined from the position of the search coil required for maximum or minimum currents induced in it.

With this system it is possible to use large, single turn, aerial loops as they have not to be rotated, but accurate adjustment of each loop to give equal electrical constants is necessary. In addition the sources of error present in the single rotating coil system are present in the Bellini-Tosi system.

142. The Robinson System.—A direction-finding system which is used largely in the Royal Air Force consists of two coils fixed at right angles and free to rotate about a vertical axis (Fig. 162). The two coils are connected in series, and the connections to one of them (the auxiliary coil) can be reversed. The E.M.F. induced in the auxiliary coil can, therefore, be added to or subtracted from that induced in the main coil. When the auxiliary coil is at right angles to the direction of the wave no E.M.F. is induced in it, and, therefore, reversing the switch causes no change in the strength of the signals picked up by the main coil.

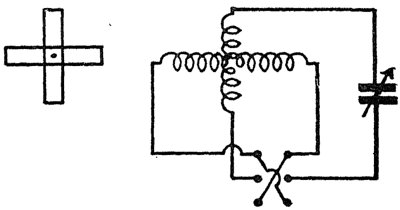


Fig. 162.

The above method is specially suitable where there are large external noises, as in aeroplanes, as the position for minimum signals has not to be determined.

143. Comparison of the Three Systems.—All the three direction-finding systems described are based on the same fundamental principle, and their accuracy is of the same order. The Bellini-Tosi system is specially suitable where it

is possible to erect large aerials, as on shore or in large ships, but where space is limited, as in aeroplanes, the Robinson system and the single rotating coil system are most suitable, the former especially where there are external noises, and the latter especially where cheapness and portability are required.

144. Sources of Errors.—In addition to the errors introduced by "vertical," inductance of leads, instrumental errors, etc., already referred to, there are several important sources of error which may render accurate direction-finding impossible. Some of these are constant errors for a given installation, and can be allowed for by plotting a curve of errors. Others are variable and difficult to allow for, and not yet fully understood.

These sources of error will only be considered briefly here, but the reader who desires to study the subject more fully will find quite a number of interesting papers on direction-finding in the journals of the various technical institutions.*

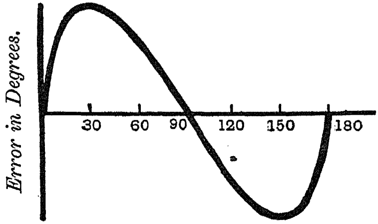
A large number of direction-finding sets are installed in ships and aeroplanes where certain difficulties are encountered that are not present as a rule in a station on shore. It is found that the metalwork present on a ship or aeroplane has currents induced in it which produce magnetic and electric fields which act on the aerials of the direction-finding set. E.M.F.'s are, therefore, induced in the latter directly by the incoming wave, and indirectly by it through the metalwork in the vicinity. In addition, the shape of the metalwork may cause the coils to be screened from waves arriving from certain directions. The effect of the metalwork is to crowd all readings towards the fore and aft line, and, owing to the currents induced in the metalwork being greater at higher frequencies, accurate D.F. work on short waves is impossible.

Fig. 163 shows a typical correction curve for a steel ship,

* For example, "Direction and Position Finding," by Captain H. J. Round—*Journal I.E.E.*, Vol. 58, p. 224, March 1920; "The Effect of Local Conditions on Radio Direction-Finding Installations," by R. L. Smith-Rose and R. H. Barfield—*J.I.E.E.*, Vol. 61, p. 179, January 1923; "Directional Wireless Telegraphy in Aircraft," by C. K. Chandler—*J.I.E.E.*, Vol. 61, p. 803, July 1923; "Wireless Direction-Finding in Steel Ships," by C. E. Horton—*J.I.E.E.*, Vol. 61, p. 1049, September 1923.

the bearings being taken relative to the fore and aft line. It will be seen that there is little error in the case of waves arriving approximately fore and aft or athwartships.

The surroundings of a land direction-finding station also cause errors which are constant under normal circumstances. Such objects as hills, cliffs, trees, buildings, and overhead wires may produce serious errors, and necessitate the careful choice of the site of the station.



Readings on goniometer.
Fig. 163.

It is found that the errors produced by masses of metal which are comparable in dimensions with those of the aerials of the direction-finding set are negligible, except where the metal is within a few feet of the aerials.

Other aerials in the vicinity may produce serious errors, especially if they are tuned to the frequency of the incoming waves. It is advisable, therefore, to ensure that these aerials are not tuned to this frequency when taking bearings with the direction-finding set.

The most serious errors encountered in direction-finding are those termed **night effects.** It is found that the apparent bearings of a fixed ground station, taken from another fixed station, vary considerably at different periods of the day and night. The variations appear to follow no definite law, and corrections cannot be applied by means of a calibration curve. The exact causes of night effects have not been fully investigated, but it is thought that reflection from the Heaviside layer, and refraction through ionised portions of the atmosphere are responsible for the change in direction of the electromagnetic waves. The errors are found to be greatest at sunrise and sunset, which is what would be expected from this theory.

145. Beverage Aerial.—An aerial possessing extremely good directional properties is the Beverage horizontal wire aerial, which has been used by the Radio Corporation of

America for some time for trans-Atlantic work. A description of this type of aerial is given in a paper read by Beverage before the American Institute of Electrical Engineers.*

The action of the Beverage aerial depends on the presence of a horizontal electric field in an electromagnetic wave due to the tilting of the wave-front, caused by the imperfect conductivity of the surface of the earth (see Chapter II.).

In its simplest form the aerial consists of a long horizontal wire, of the order of half a wave-length or more in length, suspended on poles so that it points in the direction of the incoming waves to be received. When an incoming wave reaches the end of the aerial nearest the transmitting station a small E.M.F. is induced by the horizontal electric field, and a current is set up in the wire. The conditions are then similar to those described in Chaps. II., XIII. for the transmission of electromagnetic waves along wires, and the value of the current will vary along the line, the values at points which are one wave-length apart being the same.

The velocity of the wave along the wire is approximately equal to that of light, but the insulating supports may cause a slight difference, which is negligible in most practical cases.

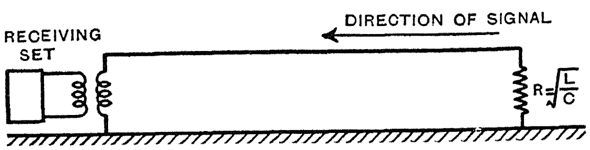


Fig. 164.

While the current due to the E.M.F. at the end of the line is flowing, the wave in space is still travelling, and induces E.M.F.'s in the wire as it goes along. Since the wave in space and the wave induced in the wire are travelling with the same velocity, the amplitude of the wave along the wire increases as the far end is approached. At the far end the receiving apparatus is placed (Fig. 164).

* See abstract in *The Electrician*, Vol. XCI., p. 269, September 14th, 1923. Also article by T. L. Eckersley in *The Electrician*, Vol. XCII., p. 39, January 11th, 1924.

Electromagnetic waves coming from the opposite direction set up a wave which has maximum amplitude at the opposite end to that at which the receiving apparatus is placed. In order to prevent reflection of this wave, with consequent effect on the receiving apparatus, a resistance is placed between the end of the line and earth to absorb the energy. The value of this resistance is equal to the characteristic impedance of the line, which again is equal to $\sqrt{L/C}$, where L and C are the inductance and capacity respectively of the line per unit length. A unidirectional aerial is, therefore, obtained by this arrangement. In addition, the aerial is a-periodic, *i.e.* no tuning is required for different wave-lengths; consequently, the aerial can be used for several wave-lengths at once, and the various sets of receiving apparatus tuned to the separate wave-lengths. For maximum efficiency, however, the various transmitting stations must be in approximately the same direction.

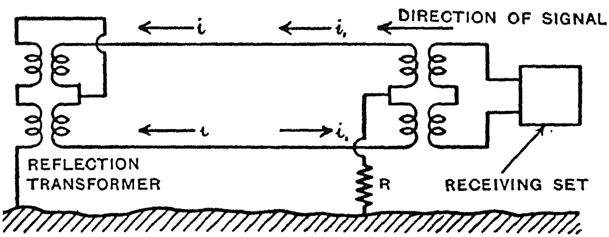


Fig. 165.

i = induced current due to signal.
i_1 = current induced by reflection transformer.

In order to enable the receiving set to be situated at the same end as the resistance to facilitate adjustment, the arrangement shown in Fig. 165 has been adopted in some cases. Two wires are used in parallel for reception, and they act as a balanced transmission line to bring the signals back to the receiving end.

In the station at Riverhead nine receiving sets have been arranged for, and six are actually in daily operation.

CHAPTER X.

AERIAL AND EARTH SYSTEMS.

146. Requirements of an Aerial System.—It will be seen from previous chapters that the chief requirements of a transmitting aerial system for good efficiency are as follows :—

(*a*) Large effective height to give good radiation.

(*b*) Large capacity to permit of large oscillations of energy, *i.e.* big aerial current, without requiring excessive voltages.

(*c*) Low resistance to reduce damping and waste of energy.

(*d*) Natural wave-length approximately equal to that of waves to be transmitted, to give maximum current and voltage in the aerial itself where they are available for radiation, instead of having energy oscillating in tuning inductances and condensers.

(*e*) Good insulation to prevent leakage and "brushing" losses.

(*f*) Minimum number of stays, masts, buildings, etc., in the immediate vicinity, where indirect currents are set up and energy dissipated.

(*g*) An efficient earth system giving good connection for the aerial current, which is a maximum at the earth end of the aerial.

(*h*) Good directive properties if the aerial is required for communication with certain fixed stations only.

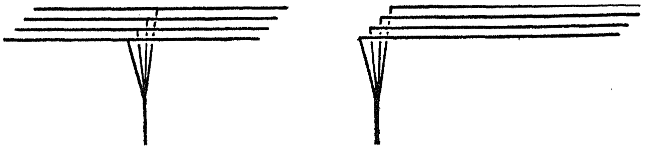
(*i*) Rigid construction to prevent variations in capacity by change in distance from earth, and to withstand wind pressure, etc.

(*j*) Suitable construction to prevent radiation of harmonics.

The above conditions need not be fulfilled to the same extent for a receiving aerial, but it will be seen that they are mostly necessary, except that the voltages and currents dealt with are of much smaller values, and the insulation and conductivity, etc., of different parts of the system need not be so great.

For receiving purposes the advantage of having a high aerial and large capacity is not so great in a region where atmospherics are prevalent, as the increased height and large upper capacity cause the aerial system to be influenced to a greater extent by atmospherics. Loop aerials or Beverage aerials are, therefore, often used for receiving purposes where a directional aerial is desired (see Chapter IX.).

147. Various Types of Aerials.—In the early days of wireless telegraphy the advantages of a high aerial were realised, and Marconi used kites to support a single wire aerial in some of his experiments. Later it was found better to use aerials with large upper capacities on similar lines to the original Hertzian oscillator. For this reason various types of multiple wire aerials were introduced.



"T" Type. "Inverted L" Type.

Fig. 166.

Fig. 166 shows two of the most common types of aerials. The **"T"** type gives best all round radiation, and the **inverted L** type is directional in the direction away from, but in line with, the horizontal portion, especially if the horizontal portion is long compared with the height, as in the Marconi bent aerial, which is of the inverted L type.

For small aerials on ships or the ground the wires forming the roof are usually supported by two masts, one at each end, and the separate wires are supported from a common

yard or **spreader** on each mast, and insulated from it. In the case of large land station aerials a separate mast may be used for each end of each wire.

In many cases a **sausage type** aerial is used instead of a flat roof aerial. In this type a large capacity is obtained by using a number of wires in the form of a cylinder (Fig. 167). Usually not more than about 10 wires are used for each

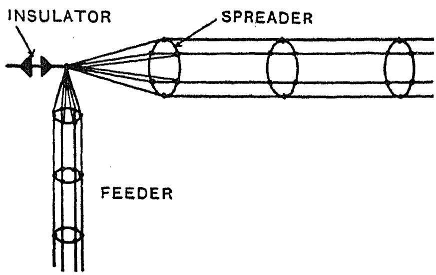


Fig. 167.

cylinder or "sausage," unless large diameter sausages are used, as very little increase in capacity is gained by using more. A number of these **multifold** or sausage aerials may be used to form a roof aerial where a very large capacity is required. Circular or other shaped spreaders are used to keep the wires apart. These spreaders need not be insulators, as all the wires connected to the same spreader are at the same potential at that point.

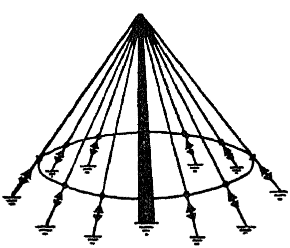


Fig. 168.

Another form of aerial which is often used is the **umbrella type,** shown in Fig. 168. This type only requires one mast, and the wires act as supporting stays. The wires are connected in parallel at the top and near the bottom, and are insulated from the mast and from the bottom ends, which are secured to the ground. The aerial of this type at the German station at Eilvese is

supported by a central mast 820 ft. high and six masts, each about 400 ft. high, surrounding the central mast in a circle 3,000 ft. in diameter. Aerial currents up to 450 amperes at a wave-length of 14,600 metres can be obtained. The aerial can be used in two parts, an upper and a lower, to enable simultaneous transmission to be carried out on 14,600 and 9,700 metres. The capacity of the upper portion is $0{\cdot}018\mu F$, and that of the lower ring is $0{\cdot}037\mu F$.

The capacity of this type of aerial is not concentrated at the top, as in the case of the "T" and inverted L types, and the radiation of energy is slower. The latter property is an advantage for C.W., as it tends to produce sharper tuning, but for spark transmission, where the duration of the wave train is short, only a small amount of energy is radiated per wave train.

In a "T" aerial the aerial feeder is taken from the electrical centre of the flat portion, otherwise the two halves would have different natural wave-lengths. If the flat portion is truly horizontal, the electrical centre is the mid-point, but if one end is higher than the other the electrical centre is nearer the lower end.

Special insulators capable of standing the strain in aerials are used to insulate the aerials from the supporting halyards. In very large aerials the effect of high winds may be very great, and the tension in the insulators may reach a value of the order of twenty thousand pounds. It will be realised that the masts for supporting the aerials have to be specially designed to withstand the severe stresses to which they are subjected (see page 196). The actual design of the masts and the calculation of the effects that are likely to be produced by wind pressures form a complicated problem, and there is very little published information on the subject. The little information that is available is very conflicting regarding the assumptions to be made for wind pressures.*

Although multiple wire aerials increase the capacity they decrease the resistance and inductance owing to the increased number of parallel paths, which also reduces brushing. The

* See "The Design of Radio Towers and Masts: Wind-Pressure Assumptions," by C. F. Elwell. *Journal I.E.E.*, Vol. 61, p. 407, March 1923.

natural wave-length of the aerial is generally increased, however, as the increased capacity more than neutralises the decrease in inductance in most cases.

It is common practice to make the individual wires of the vertical connections, or **feeders,** to the roof portion of an aerial continuous with the wires of the latter in order to eliminate resistance which would be caused by joining the wires. Phosphor-bronze wire is largely used for aerial wire on account of its strength, combined with low resistance. Copper wire is often used where great strength is not required. The wire is usually enamelled to prevent corrosion, and is composed of several strands to give mechanical strength, and also low resistance to high frequency currents.

148. Radiation from an Aerial.—The calculation of the energy radiated from an aerial with its capacity concentrated in the horizontal roof, or from a vertical wire where the capacity is uniformly distributed, is a fairly straightforward matter, and can be determined in terms of the wavelength and height of the aerial. If, however, the roof of the aerial is not horizontal, and the capacity is not distributed uniformly, the energy radiated is more difficult to calculate, and a term known as the **effective height** is introduced, which depends on the heights of the various parts of the aerial system and the distribution of the capacity. It is evident that the effective height is reduced by the close proximity of masts and buildings or other earthed objects.

The power radiated from any aerial is given by the expression:—

$$\text{Power radiated} = 1584 I^2_{\text{R.M.S.}} \times \frac{h^2}{\lambda^2} \text{watts},$$

where $I_{\text{R.M.S.}}$ is the "root mean square" value of the current at the base of the aerial, h is the effective height of the aerial and λ is the wave length.

For an aerial with large horizontal upper capacity the average energy radiated per second $= 1584 I^2_{\text{R.M.S.}} \times \dfrac{h^2}{\lambda^2}$ watts where h is the actual height of the roof of the aerial.

For a vertical wire with no added capacity the energy

radiated per second $= 640 I^2_{\text{R.M.S.}} \times \frac{h^2}{\lambda^2}$ watts where h is the actual height.

The necessity for high aerials for use on long wave-lengths will be seen from the above formulae. For short waves roof aerials cannot be used, as the height of aerial necessary for effective radiation has a long enough natural wave-length without increasing the capacity by adding a roof.

149. Effective Resistance of an Aerial.—The effective resistance of an aerial is made up of the ohmic resistance, which may be taken to include the apparent resistance due to losses in the aerial circuit, and the radiation resistance. The latter is the apparent resistance, which when multiplied by the square of the R.M.S. value of the oscillatory current at the foot of the aerial, gives the power radiated. It may be looked upon as the resistance which when placed at the foot of the aerial would dissipate the energy radiated.

For any aerial the radiation resistance is therefore given by the expression

$$\text{Radiation resistance} = 1584 \frac{h^2}{\lambda^2} \text{ ohms}$$

where h is the effective height of the aerial, since the power radiated is equal to $1584 I^2_{\text{R.M.S.}} \times \frac{h^2}{\lambda^2}$.

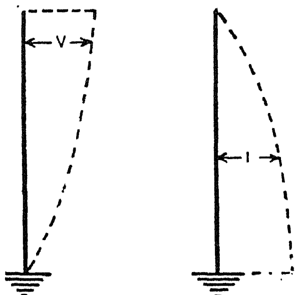
The total effective resistance determines the damping in the aerial circuit. It is therefore evident that the ohmic resistance of the aerial should be kept as low as possible. For this reason a number of wires used in parallel in the aerial is an advantage. It is also important that all connections should have low resistance to high frequency current.

Abraham gives the radiation resistance of a vertical loop aerial of area S and number of turns T as $\frac{63000 S^2 T^2}{\lambda^4}$ ohms.*

150. Distribution of Current and Voltage.—In the case of a vertical single wire aerial it is obvious that as the capacity to earth is distributed along the wire, the upper end will have the maximum voltage to earth. The distribution

* *Jahr. d. dr. Teleg.*, August 1919.

of voltage is indicated in Fig. 169 (*a*). The instantaneous value of the voltage at the upper end will vary between a maximum above earth and a maximum below earth, and the instantaneous voltage at any other point in the aerial will vary similarly between smaller maximum values.



(*a*) Fig. 169. (*b*)

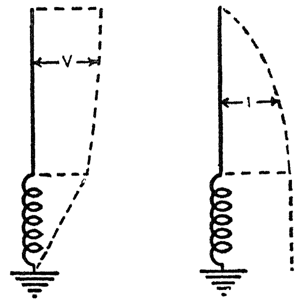
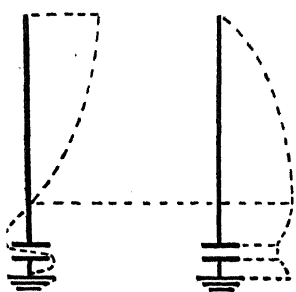


Fig. 170.

Similarly the current at the upper end of the aerial will always be zero, and will be a maximum at the foot of the aerial, as indicated in Fig. 169 (*b*).



(*a*) Fig. 171. (*b*)

It will be seen, therefore, that the upper end of the aerial requires good insulation from earth, and that the lower end requires a low resistance connection to earth if losses are to be kept small.

If an inductance be inserted at the foot of the aerial there will be a large voltage across it, and the current through it will be constant as indicated in Fig. 170.

A condenser connected in series with the lower portion of the aerial causes a reversal of the sign of the voltage and gives a point of zero voltage a little way up the aerial as shown in Fig. 171(*a*). The distribution of current is shown in Fig. 171(*b*).

Fig. 172 illustrates the distribution of current and voltage in an aerial with a large upper capacity.

If an aerial be considered as an alternating current transmission line (see Chapter II.) it will be seen that in the case of a single wire aerial with no added inductance or capacity the height of the aerial corresponds to one quarter of the wave-length.

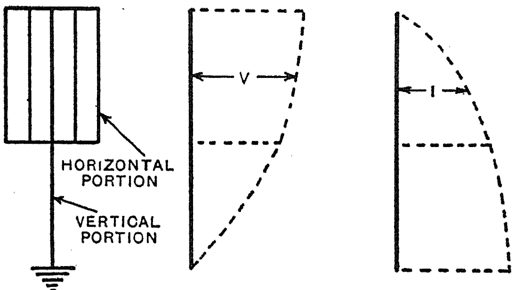


Fig. 172.

If harmonics are present in the source of oscillatory power they will produce oscillatory currents and voltages of frequencies higher than the fundamental. Fig. 173 illustrates the distribution of voltage and current due to an oscillatory current whose frequency is three times that of the fundamental.

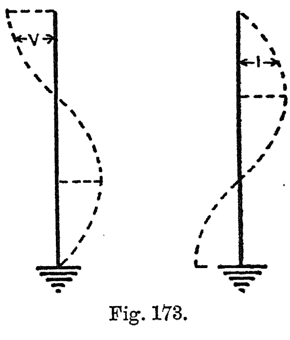


Fig. 173.

The aerial itself may produce harmonics by oscillating at harmonic frequencies, just as a violin string may vibrate at a frequency higher than its fundamental. In such cases, however, the upper end of the aerial must be a loop of voltage and a node of current and the lower end must be a node of voltage and a loop of current; consequently only odd harmonics can be produced by harmonic oscillation of the aerial.

The current in an aerial is measured at the foot of the aerial, as being the most convenient, and the aerial ammeter is usually in the earth connection. It should be noted that a large aerial current does not necessarily mean large radiation, as the effective height of the aerial may be low, owing to parts of the aerial being close to earthed objects.

If the potential gradient near an aerial wire is very high a brush discharge will take place and energy will be dissipated. A multiple wire aerial is therefore better than a single wire aerial from this point of view. Special shields or guard rings are also usually fitted on the aerial insulators to give a uniform potential gradient between the ends of the aerial wires and the masts or halyards. This prevents brush discharge and severe stresses in the insulators which might otherwise be caused if the electric field were concentrated at one or two points on the insulators. (See page 196).

151. Effect of Masts and Buildings, etc.—In addition to reducing the effective height of an aerial, masts, buildings, etc., in the vicinity of the aerial may cause large losses.

Induced currents are set up which may cause large losses if the resistance of the paths of these currents is not kept very low, and fires may be caused if special precautions are not carried out to prevent sparking and excessive induced currents.

The induced currents will cause energy to be re-radiated from the conductors in which they flow, so that if the resistance of these conductors is kept low only a small portion of the energy due to the induced currents is wasted. This radiation from mast, stays, etc., may produce harmonics, but it is difficult to determine the exact source of harmonics present in wireless telegraphy and telephony, and there is little information available as to the part played by radiation from induced currents in objects near the aerial.

The usual practice is to divide all mast stays into sections by means of insulators, and to earth the lower ends of the stays very carefully. In high power stations, however, it is found that the insulators may brush over if heavy currents are used in the aerial, and the intense heat produced causes the insulators to crumble away eventually. In some cases the insulators have been omitted and no appreciable decrease

in the radiation has been noticed. Even when an object close to the aerial is well insulated from earth brushing may occur from parts of the aerial, but this is not so great as when the object is earthed.

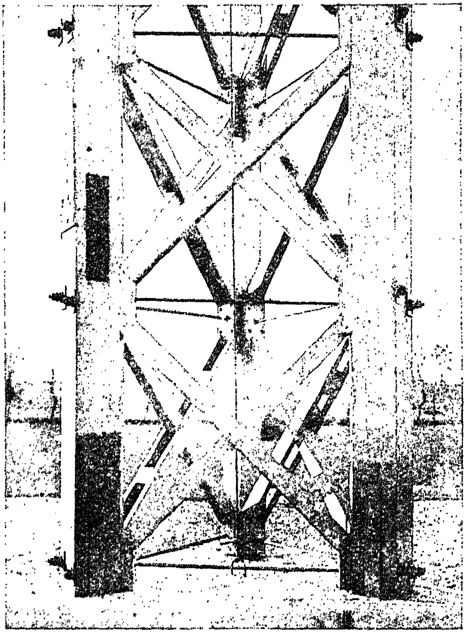


Fig. 174.

When an aerial is used for reception the presence of masts, buildings, trees, overhead wires, etc., causes the aerial to be screened owing to a large amount of the energy in the incoming waves being absorbed before it reaches the aerial. The energy absorbed may be dissipated in resistance or may be re-radiated, but in either case the aerial is screened to a large extent. It is desirable, therefore, to divide stays, etc., into insulated sections in the vicinity of a receiving aerial, and to avoid, as far as possible, fitting a receiving aerial in the vicinity of buildings and trees, etc.

Masts are either well insulated from earth or well earthed. The latter method is adopted where the difficulty of insulating the masts is too great.

152. Types of Aerial Masts.—On board ship the design of masts for purely wireless purposes does not usually arise, as the ship's ordinary masts can generally be utilised.

For small shore stations, wooden masts or tubular metal masts built in sections are usually employed.

Various types of masts are used for high power stations, and include wooden lattice masts, supported by guys, and rigid steel towers.

Wooden lattice masts are very largely used, as they are comparatively cheap and have been found very satisfactory. Masts of this type have been constructed up to six or seven hundred feet high. Fig. 174 shows the construction of a typical wooden lattice mast as designed and constructed by C. F. Elwell. This particular mast was erected in Rome in 1917 and is the highest wooden structure in the world, being 714 feet high.

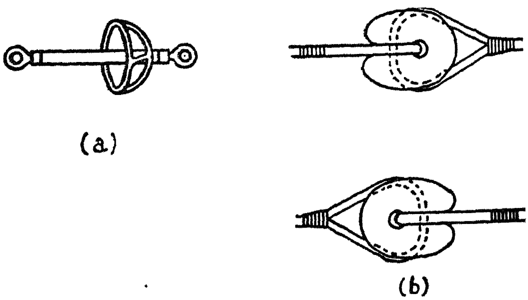


Fig. 175.

153. Aerial Insulators.—Rubber or hard wood strain insulators are often used for receiving aerials and very low power transmitting aerials. Rubber insulators have also been used for transmitting aerials for medium power spark installations, but they are not suitable for C.W. transmission, as the constant stresses produced in the latter case cause the rubber to decompose.

The substance most used for aerial insulators is porcelain. Fig. 175 (*a*) shows a typical porcelain insulator suitable for a working strain of 30 cwt. The metal guard is employed to produce a uniform potential stress.

Fig. 175 (*b*) shows a typical insulator used for insulating wire rope stays. The porcelain is in compression, and should it break the two parts of the wire rope stay will not part.

154. Earth Systems.—The method of connecting the aerial to earth plays an important part in the efficiency of an aerial system. There is still a large amount of controversy regarding the most efficient system to use, and several methods have been employed.*

In Hertz's original experiments the earth was not made use of, and the open oscillator was composed of two metal plates insulated from earth. This principle was favoured by Lodge,† who advocated avoidance of the use of the earth as one plate of the condenser, and the use of an insulated capacity area instead. This system is known as the **balanced aerial** or **counterpoise** arrangement, and has many supporters.

Marconi introduced the earthed aerial, and made commercial wireless telegraphy practicable with this system. There appears to be a tendency, however, to return to the balanced aerial system in many cases, and a number of stations have been so fitted.

When the earth is used as one plate of the condenser of the open oscillator, the circuit for the high frequency oscillation in the aerial is completed through the earth. It is most important, therefore, that there should be low resistance connection between the aerial and the earth if losses are to be kept low.

Owing to the resistance of the earth itself large losses occur if the aerial current has to flow through the earth for any appreciable distance. It is necessary, therefore, for the earthing connection to be carried horizontally as far as any points where earth currents flowing back to the aerial

* See "An Investigation of Transmitting Aerial Resistances," by T. L. Eckersley and the discussion thereon. *Journal I.E.E.*, Vol. 60, p. 581, May 1922.

† *Proceedings of the Royal Society*, Vol. 82, 1909.

system are likely to be present. Obviously, the area affected is that underneath an aerial with a flat roof, and is one extending a distance of the order of the height of the aerial in the case of a vertical aerial.

In practice earth wires are run radially over the whole of the area, and usually a little beyond. In some cases the wires are totally buried in the ground, in others they are run above the ground, high enough to enable a person to walk underneath, and connected to earth plates at the end distant from the aerial feeder. If they are not connected to earth plates in the latter case they form the lower half of a balanced aerial. This insulated arrangement is sometimes called an **aerial screen,** as it prevents energy flowing into the earth and being lost. An investigation of the effect of screens of this nature on the resistance of an aerial and the reduction of losses has been carried out by T. L. Eckersley,* who found that the losses were greatly reduced by screening the aerial in this manner.

The reduction of losses in an aerial system transmitting long waves is a most important problem, as the losses are very high, owing to the impracticability of constructing aerials of the required height for the long waves used.

An aerial screen has been introduced at Clifden, and Eckersley states that the resistance of the aerial was reduced from about 4·5 ohms to 0·6-0·7 ohms by this means. Previously a buried wire earth was used.

At the French station at Sainte-Assise a "T" aerial, with a total length of 2·8 km., is supported on 16 steel lattice masts which are uninsulated. The multiple earth system employed consists of 42 earth plates, 16 of which are at the feet of the masts, and 26 are distributed under the aerial. The earth plates are connected to the transmitting station by 12 collecting wires which run the whole length of the aerial at a height of 16 feet. These wires also act to some extent as an earth screen. In order to ensure that the current is suitably divided between the various earth wires, large inductances are inserted in the earth connections which have a short return path and smaller inductances in the earth connections which have a longer return path. To prevent excessive

* See *Journal I.E.E.*, Vol. 60, p. 581, 1922.

voltages at the station ends of the connecting wires, and to reduce the size of the inductances required, series condensers are inserted at various points in the collecting wires.

At a wave-length of 14,300 metres the total effective resistance of the Sainte-Assise aerial is 0·54 ohms, made up as follows:—

Radiation resistance	0·19 ohms
Tuning inductance	0·10 „
Aerial wires	0·05 „
Earthing system	0·20 „
Total	0·54 „

which corresponds to an aerial efficiency of $\frac{0{\cdot}19}{0.54} = 0{\cdot}35$.

In aeroplanes and airships it is, of course, impossible to use an earth, so balanced aerials are employed. In ships, especially modern steel ships, a good earth is readily obtained.

CHAPTER XI.

RANGE OF WIRELESS STATIONS.

155. Preliminary Design of a Transmitting Station.—When considering the design of a wireless transmitting station, the one definite requirement that is usually known with certainty is the range of communication required.

The reliable range that can be obtained with a given transmitting station depends, of course, on the sensitivity of the installation at the receiving station or stations with which the transmitting station is required to communicate. Some assumption has to be made, therefore, as regards the receiving station.

Assuming the energy required in the receiving aerial for reliable communication under all atmospheric conditions is known, the problem before the engineer is that of determining the power required to be radiated at the transmitting station in order to produce this amount in the receiving aerial at a given distance away. This will not be the same by any means for all receiving stations at equal distances from the transmitting station, but will depend largely on the nature of the intervening surface of the earth.

The amount of energy radiated from the transmitting aerial will depend on the effective height of the aerial, the wave-length employed, and the current in the aerial. The most suitable values for these three factors have then to be determined.

156. Energy Required in Receiving Aerial.—With modern amplifiers the amount of energy necessary in a receiving aerial is not so important as the ratio of the strength of the signals produced by this energy to the strength of atmospherics. Very weak signals can be amplified to sufficient strength, but atmospherics are also amplified

at the same time, so it is most important that the energy received in the aerial should be sufficiently large compared with that due to interfering sources such as atmospherics.

Since atmospherics are very much more serious in the tropics than in other parts of the world, it follows that the actual amount of energy received in an aerial from a wireless signal must be greatest in the case of stations in the tropics.

If atmospherics and interference from other stations could be entirely eliminated, the power of transmitting stations could be enormously reduced, but with the receiving apparatus so far designed it is necessary to provide sufficient energy in the receiving aerial to overcome these disturbances.

Another important factor influencing the amount of energy required in a receiving aerial, especially for long range communication, is the number of hours a day during which reliable communication is required. If communication can be limited to parts of the day during which atmospherics are comparatively weak, less power is required than if communication is required at all hours.

It will be seen, therefore, that the determination of the energy required in a receiving aerial is by no means a simple matter. There is a great difference of opinion as to the actual values of the signal strength required for reliable communication, and several attempts have been made to make actual measurements of the power required at the receiving station.

There is a tendency to give the strength of the field required in the neighbourhood of the receiving station instead of the power required in the aerial, and it appears likely that wireless engineers will, in future, take the field strength required at the receiving station as the basis of their calculations. Professor Vallauri measured the field strength of signals produced at Leghorn from Annapolis, and found that energies of $0{\cdot}1 \times 10^{-10}$ watts to 1×10^{-10} watts could be detected by using an 8 valve amplifier.* Professor Howe gives a figure of 0·37 microvolt per cm. as the field strength required for long range commercial communi-

* *Proceedings of the Institution of Radio Engineers*, 1920, Vol. 8, p. 286.

cation at all times, except during local thunderstorms.* This corresponds to a figure of 400×10^{-10} watts. Dr. L. W. Austin gives a minimum of 6×10^{-10} watts as necessary for regular communication round about Washington.†

Attempts are being made to standardise a method of measuring field strength, and to obtain reliable data, so that actual field strengths required in different parts of the earth for reliable communication can be determined.

157. Energy Radiated from Transmitting Aerial.— Several formulae have been employed for determining the energy required to be radiated from a transmitting aerial in order to produce a given amount of energy in a receiving aerial situated at a certain distance away.

It can be shown mathematically that the energy radiated from an aerial with large upper capacity is given by the expression :—

$$\text{Energy radiated} = 1584 \frac{h_1^2}{\lambda^2} I_1^2 \text{ watts}$$ (see also page 190),

where h_1 = effective height of aerial in metres, λ = wave-length in metres, and I_1 = R.M.S. value of current at foot of aerial in amperes.

This produces a magnetic field of strength H which is equal to the electric field E at the same point a distance d from the transmitting aerial. Then :—

$$E = H = \frac{4\pi}{10} \cdot \frac{h_1}{\lambda} \cdot \frac{I_1}{d} \times 300 \text{ volts per cm.}$$

This will produce an E.M.F. in a similar receiving aerial with large upper capacity of effective height h_2, whose value will be equal to $120\pi \frac{h_1 h_2}{\lambda d} I_1$ volts. If R is the total resistance of the receiving aerial circuit the received current I_2 will be given by the formula :—

$$\text{Current} = I_2 = \frac{120\pi h_1 h_2}{R \times \lambda d} \cdot I_1.$$

* G. W. O. Howe : *Radio Review*, 1920, Vol. 1, p. 599.

† See "Discussion on Long-Distance Wireless Transmission." *Journal I.E.E.*, Vol. 59, p. 302, June 1921.

This formula is usually given in the form :—

$$h_1 I_1 = \frac{\lambda d R I_2}{377 h_2},$$

where :—I_1 = R.M.S. value of current in transmitting aerial measured in amperes at foot of aerial.

I_2 = R.M.S. value of current in receiving aerial measured in amperes at foot of aerial.

h_1 = effective height of transmitting aerial in metres.

h_2 = effective height of receiving aerial in metres.

λ = wave-length in metres.

d = distance in metres.

R = total resistance of receiving circuit in ohms.

The above is a purely theoretical formula which makes no allowance for absorption of energy due to the resistance of the earth. It is found to be fairly accurate for distances up to 50 miles.

For longer distances it is necessary to introduce a factor to allow for the effect of the earth, and the Austin-Cohen formula has a factor as follows :—

$$\sqrt{\left(\frac{\sin\theta}{\theta}\right)} e^{0\cdot0015d/\sqrt{\lambda}},$$

where θ is the angle subtended at the centre of the earth by the sector representing the distance between the two stations. The Austin-Cohen formula * is, therefore :—

$$h_1 I_1 = \frac{\lambda d R I_2}{377 h_2} \sqrt{\left(\frac{\sin\theta}{\theta}\right)} e^{0\cdot0015d/\sqrt{}} .$$

This formula was derived empirically from the results obtained in a series of experiments between Brant Rock and U.S. cruisers in the Atlantic Ocean in 1909-10, and was tested at the time up to a range of 1,100 miles, using damped waves. It is usually taken as being fairly accurate up to about 2,200 miles.

* L. W. Austin: *Bulletin of the Bureau of Standards*, Vol. II., p. 69, 1914.

Another form in which the formula is written is :—

$$I_2R = \frac{377h_1h_2I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}e^{-0\cdot0015d/\sqrt{\lambda}}$$

$$= \text{E.M.F. induced in receiving aerial.}$$

If the formula is required in terms of field strength then the R.M.S. value of the electric field strength in volts per cm. is given by :—

$$E = \frac{377h_1I_1}{\lambda d}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}e^{-0\cdot0015d/\sqrt{\lambda}}.$$

Other formulae of a similar nature have been suggested, but the one best known is that due to Dr. Fuller, who carried out a series of experiments, using arc transmission.* Fuller gives 0·0045 instead of 0·0015 in the coefficient of e, but changes $\sqrt{\lambda}$ to $\lambda^{1\cdot4}$; thus :—

$$I_2 = \frac{377h_1h_2I_1}{\lambda dR}\sqrt{\left(\frac{\theta}{\sin\theta}\right)}e^{-0\cdot0045d/\lambda^{1\cdot4}}.$$

These transmission formulae are not very satisfactory for ranges above two or three thousand miles, but so far a more accurate formula does not appear to have been evolved. It is open to question whether an entirely satisfactory formula can be obtained which will make due allowances for the varying effects produced by curvature of the earth, absorption of the medium, and reflection from the Heaviside layer. The Austin-Cohen and Fuller formulae do, however, form a rough basis for calculating the power required in an aerial for long range transmission and a more accurate basis for shorter range calculations.

The power radiated from an aerial depends on the effective height of the aerial, the aerial current, and the wave-length, as shown by the formulae. It is necessary, therefore, to determine the best values of these quantities when designing a wireless transmitting station. Various considerations have to be taken into account, such as cost of high masts, cost of the various types of transmitting sets, and range of wave-

* L. F. Fuller : *Transactions of the American Institute of Electrical Engineers*, Vol. 34, Part I., p. 809, 1915.

lengths permissible to prevent interference with other stations, before the values to be adopted can be determined.

It is now usual to give the effectiveness of a station as the product of the effective height of the aerial and the aerial current for a given frequency, instead of the previous method of giving a meaningless number of kilowatts, which was supposed to represent the power supplied to the aerial.

Further consideration of the subject is beyond the scope of this book, but the reader who desires further information on the subject is referred to the various publications to which reference has been made in this chapter, and to more advanced books on wireless telegraphy and telephony.

CHAPTER XII.

HIGH FREQUENCY MEASUREMENTS AND PRINCIPLES OF DESIGN.

158. Difficulties Encountered in High Frequency Measurements.—Most of the methods used for ordinary low frequency alternating current measurements are unsuitable for measurements at the high frequencies used in wireless telegraphy and telephony. Apart from the high frequencies used in the latter cases there may be a very wide range of frequencies, and special precautions have to be taken to ensure accurate measurements at all the frequencies employed.

Stray capacities and inductive coupling become very important at these high frequencies, and skin effect causes resistances to have a greater value at high frequencies than at lower frequencies. If the introduction of measuring instruments into oscillatory circuits causes appreciable increased damping, the conditions may be changed so much that accurate measurements cannot be made, and large losses may occur also. In many cases extremely small amounts of energy are dealt with and specially sensitive instruments have to be employed.

159. Measurement of High Frequency Currents.—Electro-magnetic instruments cannot be employed for even moderately accurate measurements of high frequency currents, on account of their high inductance and resistance and the large damping that would be introduced into the circuit.

Hot-wire ammeters are the only instruments generally employed for the measurement of *large* high frequency currents. The wire used in hot wire ammeters must be of small diameter to ensure constant resistance at all frequencies. Shunts are usually avoided as they introduce errors, and special air core current transformers are generally employed

where the current is too large to pass through the ammeter direct. Hot wire ammeters are largely used in aerial circuits to give an indication of the amount of current in the aerial rather than to give an accurate R.M.S. value of the current.

An advantage of hot wire ammeters is that they can be calibrated by means of direct current or low frequency alternating current, provided that they are suitably designed to have approximately constant resistance at all frequencies.

Several types of instruments are employed for detection and measurement of *small* high frequency currents, the most common being those of the thermal type employing one or more thermo-electric junctions. In this thermal type of instrument, several forms of which exist, the high frequency current passes through a heater, and the rise in temperature produced affects one or more fine thermo-junctions and produces a deflection of a sensitive moving-coil galvanometer. The galvanometer is calibrated by passing direct current through the heater. In some instruments the thermo-junction lies close to, but does not touch the heater. In other instruments the thermo-junction is soldered to the centre of the heater and the whole is enclosed in an exhausted bulb.

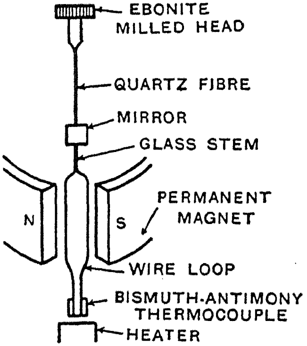


Fig. 176.

The heater usually consists of a fine wire or strip of manganin or similar substance, and several wires or strips may be connected in parallel for larger currents. For small currents the heaters may consist of a deposit of platinum or quartz or mica. Several heaters of different current carrying capacity are usually supplied with each instrument.

Non-inductive shunts are sometimes used with these instruments, but for very high frequency measurements the value of the resistance at the frequency used must be known if accurate measurements are required.

The thermo-junction usually consists of iron and eureka or

iron and special alloys. If it is enclosed with the heater in a highly exhausted glass bulb the whole is generally known as a **vacuo-junction.**

The **Duddell type of thermo-galvanometer** has practically no self inductance or capacity and is an extremely sensitive instrument for measuring small alternating currents down to twenty microamperes of any frequency. Fig. 176 illustrates the principle of the Duddell thermo-galvanometer.

The **Duddell thermo-ammeter** is a modification of the Duddell thermo-galvanometer to produce a pivoted moving coil instrument with a pointer and scale. Multi-range milliammeters are constructed with several vacuo-junctions and switching arrangements to enable any one of these to be used. The scale is calibrated to read directly in milliamperes.

The Moullin voltmeter can be used for measuring high frequency currents of low values by measuring the P.D. across a known inductance and capacity. (See page 209).

160. Measurement of High Frequency Voltages.—The accurate measurement of high voltages at high frequencies is not a simple matter and is not very often undertaken. It is possible to calculate the voltage in most cases if the current is known.

One method of measuring the peak voltages in a high frequency oscillatory circuit is by means of an adjustable spark gap calibrated by using low frequency alternating current and an A.C. voltmeter. Special precautions have to be taken to get measurements of much value. The sparking surfaces must be kept clean and must have a fairly large radius of curvature.

Electrostatic voltmeters for measuring the R.M.S. value of the voltage absorb quite a lot of energy at high frequencies, and sparking occurs if the vanes are not far apart. If the distance between the vanes is sufficient to prevent sparking the electric field is usually too weak for satisfactory working.

The accurate measurement of high frequency voltages of small value is very often required, *e.g.* in measurement of signal strength and the value of inductances. An instrument that is now being largely used for this purpose is the

Moullin thermionic voltmeter.* The Moullin voltmeter depends for its action on the rectifying properties of a three electrode valve, and absorbs practically no power from the circuit and possesses negligible capacity. It is also suitable for use at all frequencies.

An alternating E.M.F. applied between the grid and filament of a three electrode valve produces a rectified current in the anode circuit, and the amount of this current can be measured by means of a galvanometer, thus giving a measure of the applied E.M.F. Either the anode current-grid potential characteristic, or the grid current-grid potential characteristic can be used to produce rectification.

Even when no E.M.F. is applied between the grid and the filament a certain amount of anode current and possibly grid current will be flowing. It is necessary, therefore, for the rectified current to be comparable in magnitude with the permanent current, if the value of the applied E.M.F. is to be determined by measuring the deflection produced on a galvanometer by the rectified current. This condition may be obtained by suitable adjustment of the anode voltage. If the curvature of the anode current-grid potential characteristic is used for rectification this condition is fulfilled if no anode battery is employed.

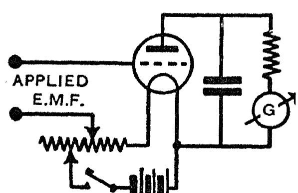


Fig. 177.

Fig. 177 illustrates the connections of one form of the Moullin voltmeter which works on the anode current-grid potential curve for rectification. The resistance in series with the 6-volt battery enables the grid to be kept at a potential of 1·6 volts negative to the filament to keep grid damping small, and allows only 3·6 volts to be applied to the filament to prevent ageing of the valve.

The correctness of the calibration depends entirely on the grid current, and the instrument is adjusted by means of the filament rheostat so that the pointer of the galvanometer is

*See "A Direct Reading Thermionic Voltmeter and its Applications," by E. B. Moullin, *Journal I.E.E.*, Vol. 61, p. 295, February 1923. Also *Wireless World and Radio Review*, 1922, Vol. 10, p. 1.

at zero when there is no applied E.M.F. Under this condition the value of any applied E.M.F. can be read off the scale directly in volts. It is necessary for adjustment of the zero that the applied E.M.F. terminals be connected together to obtain the correct grid potential. For the same reason the instrument can only be used to measure E.M.F.'s across a conducting path, and cannot be used to measure the E.M.F. across a condenser if the circuit contains another condenser in series. Nor can it be used if a steady external voltage in addition to the alternating E.M.F. exists between the grid and filament.

The other form of Moullin voltmeter, known as Type B, works on the grid current-grid potential curve for rectification and can be used for measuring either alternating E.M.F.'s superposed on a steady E.M.F., or E.M.F.'s across apparatus which does not form part of a closed conducting circuit.

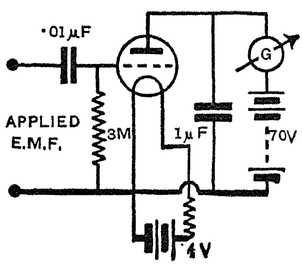


Fig. 178.

A diagram of connections of the Type B voltmeter is shown in Fig. 178. A 4-volt battery is used in this case and a filament resistance cuts down the voltage to 3·6 volts across the filament. A 70-volt anode battery is used. The accuracy of the instrument is independent of small changes in filament and anode voltages, so provided the pointer is adjusted to zero no further precautions need be taken if the filament and anode voltages are approximately correct.

The Type A instrument has a range of 0 to 1·5 volts and the Type B instrument has a range of 0 to 10 volts.

The Moullin voltmeter can be used for a large number of purposes in addition to the measurement of voltage of any frequency. These include measurement of small currents, inductance, amplification, signal strength, etc.

161. Measurement of Power.—The only method of measuring the power in a high-frequency oscillatory circuit is to measure the R.M.S. value of the current and the value

of the effective resistance. The power is then given by the product of the latter and the square of the former.

162. Measurement of Frequency and Wave-length.—The measurement of the frequency and wave-length of a high-frequency oscillatory current or circuit is probably the most important high-frequency measurement that has to be made. It is usually carried out by means of a **wavemeter.** (See also p. 225 for Campbell's method of measuring frequency.)

For measuring the frequency of an oscillatory current the wavemeter consists of an oscillatory circuit very loosely coupled to the circuit in which the current is passing. The values of the inductance and capacity in the wavemeter are adjusted until the wavemeter is in resonance with the circuit carrying the current. This is shown by some device which indicates when the E.M.F. induced in the wavemeter is a maximum. The inductances and condensers used in the wavemeter are of known value, so the frequency can be calculated from the formula :—

$$\text{Frequency} = f = \frac{1}{2\pi\sqrt{\mathrm{LC}}} \text{ cycles per sec.,}$$

where L is in henries and C in farads ; or indirectly from the formula :—

$$\text{Wave-length} = \lambda = 1885\sqrt{\mathrm{LC}} \text{ metres,}$$

where L is in microhenries and C in microfarads.

Fig. 179 shows a wavemeter with a vacuum tube to indicate when the circuit is in resonance. There is maximum glow in the tube when resonance occurs. Instead of a vacuum tube a high-frequency milliammeter or galvanometer, or a lamp, or a crystal with a pair of telephones may be used in series with the wavemeter circuit to indicate when resonance occurs.

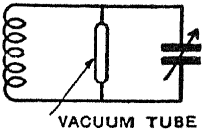


Fig. 179.

In other cases a galvanometer across a thermo-junction is used in series with the wavemeter circuit.

A wavemeter usually includes a number of standard inductances of different values, and a standard variable condenser, so that a large range of frequencies can be covered.

For measuring the natural frequency of an oscillatory circuit some means of exciting this circuit or the wavemeter circuit is necessary. The most common case is that of tuning a receiving circuit. In this case the wavemeter is adjusted to the required wave-length, and is excited by a buzzer or oscillatory valve, and is loosely coupled to the receiving circuit. The receiving circuit is then adjusted until the sound heard in the telephones is a maximum.

Accurate measurement of the inductance of the standard coils and careful calibration of the variable air condenser are necessary. In addition, the self-capacity of the coils, due to the capacity between turns, must be known and added to the capacity of the condenser to determine the total capacity in the wavemeter circuit. The coils are constructed of stranded wire to ensure constant inductance at all frequencies. The condenser must be designed so that errors are not introduced by changes in capacity due to adjacent bodies. It is usually enclosed in a metal case for this reason, and sometimes a long handle is fitted to prevent proximity of the hand affecting the capacity. The value of the inductance of the coil used for any frequency should be such as to require a large value of the capacity to give the frequency required, in order to keep any errors due to stray capacities and the self-capacity of the coil as small as possible.

163. High Frequency Inductance.—The inductance of a coil carrying high-frequency current is not necessarily the same as when the coil is carrying direct or low-frequency current, unless the coil is specially designed. This is due to differences in the distribution of the current throughout the coil depending on the frequency. In order to keep the inductance of a coil constant for all frequencies the coil is constructed of multiple-stranded insulated fine wire. This ensures the distribution of current being practically the same at all frequencies.

It is necessary, however, to take into consideration the self-capacity of the coil, which can be regarded as producing the same effect as a condenser connected between the two ends of the coil. It is evidently desirable to keep the self-capacity small, and to know its value, if an inductance is required for use essentially as an inductance of known

value. This is very important in the case of standard inductances for comparison purposes and for use in wave-meters, and is also important in the case of aerial coils for both transmitting and receiving, especially for short waves.

Another extremely important consideration in the design of an inductance for high-frequency work is the high-frequency resistance. A large high-frequency resistance means large losses and increased damping, and poor selectivity, which are of great importance in both transmitting and receiving circuits. It has been shown that the high-frequency resistance of a coil at a given frequency varies with the number of strands used and the spacing of the turns.* In fact, at very high frequencies solid conductors are shown to be preferable, and there is a certain number of strands which will give the best results for a given frequency (see p. 230).

It will be realised that the design of the most suitable high-frequency inductance for a given purpose is by no means a simple matter, and there is still a large amount of investigation required before the subject is thoroughly mastered, although a great deal of progress has been made during the last few years.

164. Types of High Frequency Inductance Coils.—Single layer coils are the most efficient inductances and have low self-capacity, as adjacent turns have very little difference of potential between them. In many cases, however, a single layer coil to give the inductance required would have prohibitive dimensions, so multi-layer coils have to be employed in such cases. Several methods are employed to wind multi-layer coils so that turns

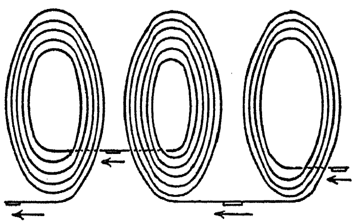


Fig. 180.

* See "The Design of Inductances for High-frequency Currents," by C. L. Fortescue, *Journal I.E.E.*, Vol. 61, p. 933, August 1923, and S. Butterworth: *Philosophical Transactions*, 1922, Vol. 222 (A), p. 57

near together have small differences of potential, and so that there is a certain amount of spacing between turns to give low self-capacity and good efficiency.

Fig. 180 shows a type of coil which is divided into sections or "slabs," the sections being connected together in such a manner that minimum P.D. occurs between turns of adjacent sections. Inductances of this type are largely used in transmitting circuits, paxolin separating pieces being used between turns and sections where high voltages and currents are used.

Fig. 181 shows the arrangement of turns in a **pile-wound** coil. The coil illustrated is a three-layer winding, and the numbers indicate the order of the turns. A pile-wound coil has one advantage over other multi-layer coils, its inductance can be calculated with sufficient accuracy for most purposes (see p. 220).

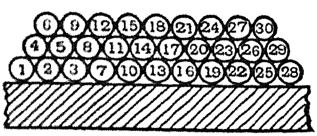


Fig. 181.

Types of coils used largely for receiving purposes are the **lattice, honeycomb,** and **duo-lateral** coils.

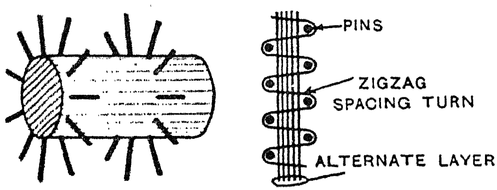


Fig. 182.

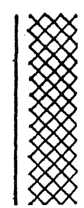


Fig. 183.

The lattice coil is made by winding a zig-zag turn round a number of pins in a former (Fig. 182), and on the completion of the turn a single layer of wire is wound round the former, followed by another zig-zag turn, and so on alternately. The coil is then soaked in paraffin wax and the former and pins removed.

Fig. 183 shows an expansion of part of a honeycomb coil. Part of a complete layer, formed by the wires crossing each other until the layer is completed, is shown. Similar layers are then wound over the first layer.

In the duo-lateral coil the turns in one layer are over the spaces between the turns in the lower layer instead of over the turns as in the honeycomb type.

165. Measurement of High Frequency Inductance.—A method largely used for measuring the value of an inductance at high frequencies is a bridge method due to **Anderson.** This method is independent of frequency, and can be used with a D.C. supply and a ballistic galvanometer, or with an A.C. supply and a suitable detector such as a vibration galvanometer or a telephone.

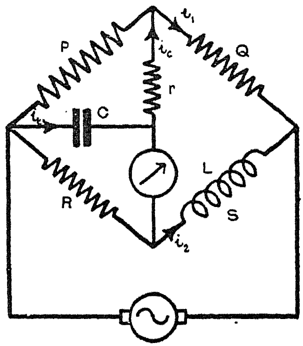


Fig. 184.

Fig. 184 shows the connections for the A.C. method generally employed, in which the value of the inductance is measured in terms of a standard condenser. P, Q, R, and r are non-inductive resistances, C is a standard condenser, and L and S are the inductance and effective resistance respectively of the coil to be measured. R and r are adjusted until a balance is obtained. Then :—

$$i_C = j\omega C V_C,$$

where $j = \sqrt{-1}$, and indicates a phase difference of 90°, and V_C = voltage across C,

and $$i_C = \omega C V_C \text{ (numerically)}.$$

$$\therefore \; V_C = \frac{i_C}{j\omega C}.$$

Also $$V_r = i_C r,$$

and $$V_P = V_C + V_r \text{ (vectorially)}$$

$$= \frac{i_C}{j\omega C} + i_C r$$

$$= i_C\left(r + \frac{1}{j\omega C}\right).$$

Now $$i_P = \frac{V_P}{P}$$
$$= \frac{i_C}{P}\left(r + \frac{1}{j\omega C}\right),$$
and $$i_1 = i_P + i_C$$
$$= V_C\left(\frac{j\omega Cr}{P} + \frac{1}{P} + j\omega C\right).$$

Also $$V_P = V_C\,(1 + j\omega Cr).$$
$$\therefore\ V = V_P + V_Q$$
$$= V_C\,(1 + j\omega r) + i_1 Q$$
$$= V_C\,(1 + j\omega Cr + j\omega Cr\,\frac{Q}{P} + \frac{Q}{P} + j\omega CQ).$$

In the lower branch :—
$$V = i_2\,(R + S + j\omega L)$$
$$= \frac{V_R}{R}\,(R + S + j\omega L),\ \text{since } i_2 = \frac{V_R}{R}.$$

Since $V_C = V_R$ for a balance,

then $$1 + j\omega Cr + j\omega Cr\,\frac{Q}{P} + \frac{Q}{P} + j\omega CQ$$
$$= 1 + \frac{S}{R} + \frac{j\omega L}{R}.$$

Equating real and imaginary parts gives :—
$$\omega CQ + \omega Cr\left(1 + \frac{Q}{P}\right) = \frac{\omega L}{R}.$$
$$\therefore\ \frac{L}{C} = Rr\left(1 + \frac{Q}{P}\right) + QR$$
$$= QR + r\,(R + S),$$
and $$1 + \frac{Q}{P} = 1 + \frac{S}{R}$$
$\therefore$ QR = SP, which was an initial condition.

Further information regarding this method of carrying out high frequency measurements is given in a paper by Butterworth.*

The **Campbell Variable Standard of Mutual Inductance** provides an easy means of measuring the value of an unknown mutual inductance within its range. An accuracy of one in a thousand is claimed for this instrument at a frequency of 1,000 cycles per second, but at higher frequencies other methods have to be employed for accurate measurements.

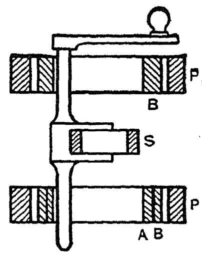


Fig. 185.

Fig. 185 illustrates the principle of the instrument.

P and P_1 are fixed primary coils connected in series.

B is a fixed secondary with tappings to give large values of mutual inductance.

A is a fixed secondary with tappings to give small values of mutual inductance.

S is a movable secondary which can be turned about an eccentric axis by means of a pointer moving over a semi-circular scale to give very small values.

S gives a range of — 3 to 104 microhenries.

A gives values of 100, 200, 300, etc., to 1,000 microhenries.

B gives values of 1,000, 2,000, 3,000, etc., to 10,000 microhenries.

Instruments to measure larger values are also in use.

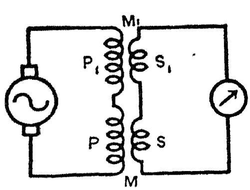


Fig. 186.

Fig. 186 shows the method of measuring the value of a mutual inductance by the method of simple opposition. The mutual inductance, M_1, to be measured is connected so that its primary, P_1, is in series with that of the Campbell Variable Mutual Standard and an A.C. source. The secondaries are connected in opposition in series with a vibration galvanometer or telephone. M is adjusted until a balance is

* S. Butterworth, *Physical Society's Proceedings*, 1921, xxxiv. I.

obtained, *i.e.* until the secondary current is zero, then $M = M_1$.

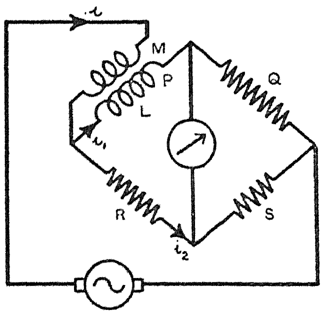


Fig. 187.

Maxwell's Bridge Method is often used for measuring the mutual inductance between two coils. Fig. 187 shows the arrangement using A.C. In some cases D.C. is used with a ballistic galvanometer and balance obtained for steady currents, and also at make and break.

$$i_1 (P + j\omega - L)\ j\omega Mi = i_2 R,$$

and $$i_2 = i - i_1.$$

$$\therefore\ i_1 (P + j\omega L) - j\omega Mi = (i - i_1)R.$$

Equating real and imaginary parts gives :—

$$i_1 \omega L = i \omega M$$

and $$i_1 (P + R) = iR,$$

$$\therefore\ \frac{L}{M} = \frac{P + R}{R}.$$

The Moullin voltmeter (page 209) has been used to measure inductances of the order of a microhenry by passing through them about half an ampere of high frequency current, and measuring the voltage across them.

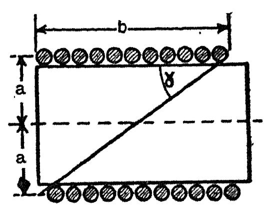


Fig. 188.

166. Calculation of the Inductance of a Coil.—The calculation of the inductance of a coil is rather complicated, owing to the necessity for taking into consideration the effect of each turn upon every other turn.

The inductance of a single layer coil is usually determined

for design purposes by a formula due to Lorentz as modified by Rosa,* viz. :—

$$L = an^2Q \text{ cms},$$

where a = mean radius of coil,

n = number of turns,

Q = a constant depending on γ, where

$$\tan \gamma = \frac{2a}{b},$$

b = length of coil (Fig. 188).

The following table gives the values of Q for various values of tan γ for a single layer coil :—

$\tan \gamma = \frac{2a}{b}$.	Q	$\tan \gamma = \frac{2a}{b}$.	Q	$\tan \gamma = \frac{2a}{b}$.	Q
0·2	3·632	1·4	16·898	3·2	26·18
0·3	5·234	1·6	18·304	3·4	26·902
0·4	6·7102	1·8	19·58	3·6	27·585
0·5	8·075	2·0	20·746	3·8	28·235
0·6	9·339	2·2	21·82	4·0	28·853
0·7	10·513	2·4	22·815	10	40·2
0·8	11·068	2·6	23·74	20	48·8
0·9	12·631	2·8	24·605	30	53·9
1·0	13·589	3·0	25·416	40	57·5
1·2	15·338				

The values of Q in the last column of the table are derived from Rayleigh and Niven's formula for short coils of large diameter. This formula is :—

$$L = 4\pi a n^2 \left\{ \log \frac{8a}{b} - \frac{1}{2} + \frac{b^2}{32a^2}\left(\log \frac{8a}{b} + \frac{1}{4}\right) \right\} \text{ cms.}$$

Dividing by 10^3 gives the inductance in microhenries.

The following table gives the values of Q for multiple

* See the *Bulletin of the Bureau of Standards*, August 1908, p. 114.

layer coils, where the winding depth is equal to t cms., for various values of $\frac{t}{2a}$.

$\frac{t}{2a}$	Values of Q.				
	$\frac{b}{2a}=0{\cdot}5.$	$\frac{b}{2a}=0{\cdot}75.$	$\frac{b}{2a}=1{\cdot}0.$	$\frac{b}{2a}=1{\cdot}25.$	$\frac{b}{2a}=1{\cdot}5.$
0·0	21·24	16·48	13·40	11·34	9·92
0·1	15·48	12·36	10·20	8·70	7·60
0·2	11·60	9·18	7·60	6·46	5·60
0·3	8·04	6·50	5·42	4·70	4·08
0·4	5·28	4·36	3·70	3·20	2·84

If the coil is wound on a former with a square cross-section its inductance will be from 22 per cent. to 27½ per cent. greater than when wound on a cylindrical former whose radius is equal to that of the circle inscribed in the square. Similarly in the case of a hexagonal former the inductance will be about 10 per cent. greater.

The reader who desires to study in more detail the design of inductances, and the effective resistance of such coils is referred to papers by Howe,* Butterworth,† and Fortescue.‡

The inductance as calculated above is that for direct current, and for all practical purposes this is correct for high frequency current, provided the self-capacity of the coil is taken into consideration and added to the external capacity connected across the coil.

An approximate formula for pile-wound multi-layer coils (see page 214) is:—

$$\underset{\text{(microhenries)}}{L} = \frac{\pi^2 D^2 N^2 P^2 lk}{1000},$$

* G. W. O. Howe: *Proceedings of the Royal Society*, 1917, Vol. 93 (A), p. 468.

† S. Butterworth: *Philosophical Transactions*, 1922, Vol. 222 (A), p. 57.

‡ C. L. Fortescue: *Journal I.E.E.*, 1923, Vol. 61, p. 933.

where D = diameter of coil in centimetres,
l = length of coil in centimetres,
N = number of turns per centimetre in any *one* of the layers,
P = number of layers or "piles" in the coil,
k = a constant whose value depends upon the ratio of the length of the coil to its diameter. Various values of k are given in the table below.

$\frac{l}{D}$	0·50	0·75	1·00	1·50	20·0	2·50	3·00	3·50	4·00	5	6
k	0·51	0·62	0·67	0·76	08·1	0·84	0·86	0·88	0·90	0·91	0·92

167. High Frequency Condensers.—The condensers used in wireless transmitting circuits may have to stand high voltages and large currents, and it is very important that their losses should be kept as low as possible to keep down the effective resistance of the circuits.

As dielectric strength is proportionately stronger for thin layers of dielectric than for thick layers, it is usual to build up large condensers in several sections connected in series for high voltages. The following table shows the approximate breakdown voltages for various dielectrics 1 millimetre thick placed between metal plates. The values given are, however, for certain samples, and should not be taken as applying generally in all cases.

Dielectric.	Breakdown Voltage.	Corresponding Sparking Distance with Air as Dielectric.
Glass	28,500 volts.	9 mm.
Indiarubber	40,000 ,,	13 mm.
Ebonite	50,000 ,,	14 mm.
Mica	60,000 ,,	20 mm.
Vaseline oil	7,000 ,,	2·4 mm.

It is usual to allow a factor of safety of from 3 to 6 in case of damage by brush discharge.

The following table shows the approximate efficiency of a condenser with different dielectrics:—

Dielectric.	*Efficiency.*
Air	100 per cent.
Oil (dry)	100 ,,
Mica (good quality)...	90 ,,
Mica (ordinary)	40-60 ,,
Ebonite (thick)	70 ,,
Glass	60 ,,

The above figures should only be considered as an illustration of the efficiency in various cases; the actual efficiency in any particular case will depend on the quality of the material used.

Condensers with ebonite or glass as the dielectric are usually immersed in oil to prevent brushing along the edges.

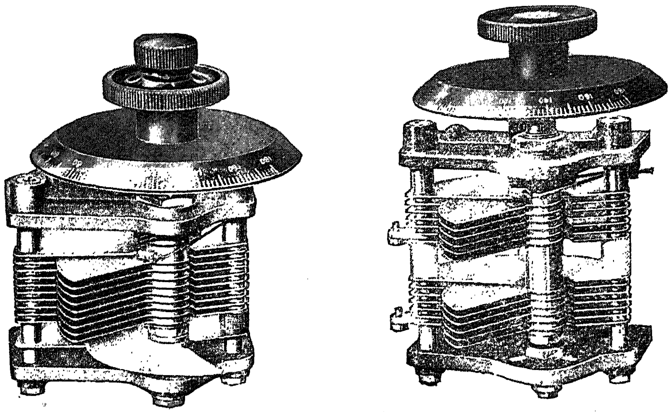


Fig. 189.

Receiving condensers should have maximum efficiency, so air is used as the dielectric except where large capacity is required. In the latter case good quality mica or ebonite is used. Oil is very often used if the condenser is variable. Fig. 189 illustrates two simple yet typical variable condensers. The fixed plates are semi-circular, the moving plates "cam"

shaped, and both are made of brass or aluminium; the set of fixed plates is connected to one terminal, and the set of moving plates to the other terminal of the condenser. Very often the condenser is mounted in a metal case to give constant capacity to earth.

At high frequencies the capacity between leads may become appreciable owing to the small values of capacity used in the circuits.

The capacity of a multiple plate condenser is given by the formula:—

$$C = \frac{KAN}{4\pi d} \text{ cm.}$$

where K = the specific inductive capacity of the dielectric,

A = area of one side of one plate in square cm.,

N = number of dielectrics under strain,

d = distance between two successive plates in cm.

Absolute units of capacity (cm.) can be converted to microfarads by dividing by 9×10^5.

The following table gives approximate values of the specific inductive capacity of various substances:—

Dielectric.	*S.I.C.*
Air	1
Ebonite	2·21 to 2·76
Glass	5 to 10 (very variable)
Mica	4 to 8 (very variable)
Porcelain	4·4 to 6·8
Shellac	2·7 to 3·7
Paper (dry)	2· to 2·8
Paraffin	1·7 to 2·3
Vaseline oil	2·0
Distilled water	83 (very low efficiency)
Indiarubber	2 to 3

168. Self-Capacity of an Inductance.—For making accurate measurements at high frequency it is essential that the self-capacity of any inductances used should be known. A method of determining the self-capacity of a coil is to find the natural frequency and the inductance of the coil. The

natural frequency can be found by placing the coil near a circuit in which high frequency current is flowing and then adjusting the frequency of the latter circuit until it is in resonance with the coil as indicated by a vacuum tube placed near the latter. The frequency of the current is then found by means of a wavemeter.*

169. Measurement of Capacity and Energy Losses of a Condenser.—An accurate method of measuring the capacity and energy losses of a condenser is that known as the **Carey Foster Bridge Method.** This is a very convenient method using Campbell's standard of mutual inductance.

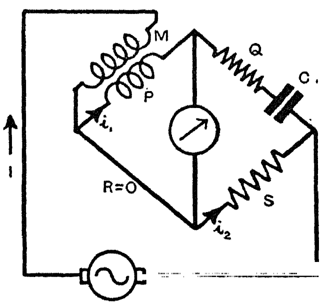


Fig. 190

The diagram of connections is shown in Fig. 190 where M represents the Campbell variable standard with a primary winding inductance equal to L. C is the capacity to be measured and Q includes the resistance of the condenser. A Carey Foster auxiliary resistance is used to introduce a resistance P of 100, 1,000, or 10,000 ohms (a big resistance for small capacity to be measured) and a resistance S of 10, 50, or 100 ohms. Q and M are varied until a balance is obtained. Then :—

$$i_1(\mathrm{P} + j\omega\mathrm{L}) - \mathrm{I}j\omega\mathrm{M} = 0,$$

$$\therefore\ i_1(\mathrm{P} + j\omega\mathrm{L} - j\omega\mathrm{M}) - i_2 j\omega\mathrm{M} = 0.$$

$$\text{Also } i_1\left(\mathrm{Q} - \frac{j}{\omega\mathrm{C}}\right) - i_2\mathrm{S} = 0,$$

$$\therefore\ \mathrm{S}\{\mathrm{P} + j\omega(\mathrm{L} - \mathrm{M})\} = j\omega\mathrm{M}\left(\mathrm{Q} - \frac{j}{\omega\mathrm{C}}\right).$$

$$\therefore\ \mathrm{SP} = \frac{\mathrm{M}}{\mathrm{C}} \quad \text{and} \quad \mathrm{S}(\mathrm{L} - \mathrm{M}) = \mathrm{MQ}.$$

* See G. W. O. Howe on "The Calibration of Wavemeters for Radio-Telegraphy," *Proceedings of the Physical Society*, Vol. xxiv., Part V., August 1912.

Q contains the effective resistance R_c of the condenser, which can therefore be determined if L is known. The power factor of a condenser is generally used to denote the effective resistance or energy losses, and is equal to $R_cC\omega$ where C is in farads, provided R_c is small compared with $\frac{1}{\omega^2C^2}$.

A more complete treatment of the Carey Foster Bridge and the consideration of errors that are liable to occur are given in a paper by S. Butterworth.*

Campbell's method of measuring large capacities or frequencies consists in balancing a mutual inductance against a condenser (Fig. 191). The inductance of the primary is N and that of the secondary L. S represents the effective resistance due to the losses in the condenser C to be measured and in the mutual inductance. The effect of S is to prevent a true balance being obtained owing to an unbalanced vector being introduced. By introducing condenser C′ (due to Butterworth) a perfect balance of the fundamental can be obtained.

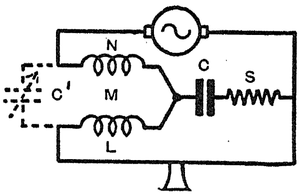


Fig. 191.

If S is small the position of minimum sound can be found to a few parts in ten thousand and the simple relation is

$$MC\omega^2 = 1,$$

where $\omega = 2\pi \times$ frequency.

Two equations have to be satisfied if C′ is used to measure S, viz. :—

$$MC\omega^2 = 1 - \frac{C'}{M}\{QR - \omega^2(L-M)(N-M)\},$$

$$S = C'\omega^2\{R(N-M) + Q(L-M)\}.$$

This method is extremely sensitive for measuring small changes in frequency. By using a small air condenser in parallel with C it is claimed that it is possible to measure

* S. Butterworth: *Phys. Soc. Proc.* 1920, xxxiii. 312.

with ease and certainty changes in frequency as small as one part in a million. It can be used to detect a harmonic of only one-ten thousandth of the amplitude of the fundamental.

Other bridge methods are used for measuring capacity, but the student is referred to text-books on the subject if further information is required.

170. Measurement of Capacity of an Aerial.—The capacity of an aerial can be determined fairly simply and accurately by means of a wavemeter. A known inductance is inserted in the aerial circuit and the change in wavelength measured. If L_1 and C_1 are the inductance and capacity respectively in the wavemeter circuit for resonance before inserting the known inductance L in the aerial circuit, and their values are L_2 and C_2 for resonance after inserting L in the aerial circuit, then

$$C_o = \frac{L_2C_2 - L_1C_1}{L}$$

where C_o is the capacity of the aerial.

171. Calculation of Aerial Capacity.—When designing an aerial it is obviously desirable to be able to estimate the capacity it will have when erected. In addition to the determination of the capacity of the aerial wires suspended freely it is necessary to determine the effect of masts and buildings if an accurate value of the aerial capacity is to be obtained.

An accurate and simple method of calculating the capacity of simple aerials is that due to Professor Howe*. This method can be used for most complex aerials with sufficient accuracy for all practical purposes. Howe bases his calculations on the following assumption. He takes the case of a long wire suspended horizontally or vertically at a large distance from earth and brought to a potential above or below earth. The electric charge will not be uniformly distributed but will have a greater density near its ends. If the wire be considered to have equal density at all points the potential will vary, and Howe assumes that the mean

* See *The Electrician*, Vol. LXXIII., p. 829, and Vol. LXXV., p. 870, Sept. 17, 1915.

potential all along the wire under these conditions will be the same as that of the wire under normal conditions of equal potential and varying density at different points.

On this assumption Howe shows that the capacity of a single wire far removed from earth is given by the formula :—

Capacity per centimetre length

$$= \frac{1}{2 \log_e \frac{l}{r} - 0{\cdot}618} \text{ E.S. units}$$

$$= \frac{1}{2 \log_e \frac{l}{r} - 0{\cdot}618} \times \frac{1}{9 \times 10^5} \text{ mfds.,}$$

or capacity per foot

$$= \frac{33{\cdot}9}{2 \log_e \frac{l}{r} - 0{\cdot}618} \text{ micro-microfarads } (\mu\mu\text{F}),$$

where l = length of wire in cm.,
r = radius of wire in cm.

For most practical cases the value lies between 1·5 and 2·1 $\mu\mu$F per foot.

The capacity of multiple wire aerials can be determined similarly by finding the potential at any point on one wire due to its own charge and the charges on the other wires, and calculating the mean of the potentials at every point, and assuming this is the actual potential of the aerial. For multiple wire flat aerials neglecting the effect of the earth Howe gives

$$\text{Capacity} = \frac{16{\cdot}94\, n}{n\left(\log_e \frac{l}{d} - 0{\cdot}31\right) + \log_e \frac{d}{r} - \text{B}} \ \mu\mu\text{F per foot,}$$

where l = length of aerial (cm.)
n = number of parallel wires equidistant.
d = distance between two wires (cm.)
B = average value of $\log_e \underline{|m-1}\ \underline{|n-m}$ for all values of m from 1 to n.

The following table gives values of B for various values of n.

No. of wires (n).	2	3	4	5	6	7	8	9	10	11	12
Value of B.	0	·46	1·24	2·26	3·48	4·85	6·4	8·06	9·8	11·65	13·58

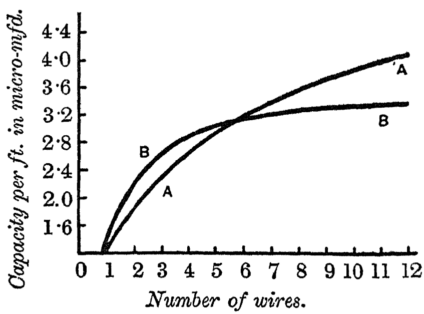


Fig. 192.

The curves given in Fig. 192 show the effect of varying the number of wires in a multiple wire flat aerial 200 feet long, and radius of wire 0·05 in. Curve A shows the effect of keeping the wires 2 ft. apart and increasing the number, and curve B shows the effect of keeping the overall width constant at 10 feet and varying the number of wires. It will be seen that there is little gain in the capacity by increasing the number of wires in a given space beyond three or four. Similarly the capacity of multiple aerials of the cylindrical or sausage type can be calculated and the results show that there is little increase in capacity if the number of wires in a given diameter of "sausage" is increased beyond about ten.

Howe calculates the effect of the earth by Kelvin's method of images. A wire suspended horizontally at a height h above the earth, and charged positively, induces negative charges on the earth, the effect of these being the same as if they were concentrated on a horizontal wire at a depth h below the surface of the earth and the earth removed

(Fig. 193). The formula given by Howe for the average potential of a wire due to a uniformly distributed charge on a parallel wire is

$$2\left(\sinh^{-1}\frac{l}{d}+\frac{d}{l}-\sqrt{1+\frac{d^2}{l^2}}\right)$$

where the charge is one unit per cm. of length. In the present case $d = 2h$ so the effect of the earth can be calculated. In the case of multiple aerials the earth effect becomes important.

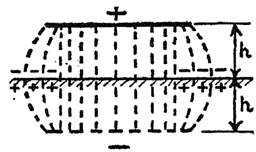


Fig. 193.

Howe gives the following formula for the capacity of a multiple wire horizontal aerial :—

Capacity in micro-microfarads per foot of span

$$= \frac{16{\cdot}94n}{n\left(\log_e\frac{l}{d} - 0{\cdot}31 - \frac{E}{2}\right) + \log_e\frac{d}{r} - B.}$$

It will be observed that the term $\frac{nE}{2}$ has been introduced into the formula on page 227 to allow for the effect of the earth. E is a function of $\frac{l}{2h}$ and various values are given in the following table :—

$\frac{l}{2h}$	0·5	0·7	1·0	2·0	3·0	5·0	7·0	10·0	15	20
E	0·48	0·67	0·94	1·64	2·19	2·98	3·56	4·2	4·9	5·46

The effect of buildings can be calculated similarly.

172. High Frequency Resistance of Wires and Coils.—The accurate measurement and calculation of the high frequency resistance of wires and coils are problems which have engaged the attention of engineers and physicists for a number of years. Both problems are complicated, and

although many valuable contributions* have been made to their solution the wireless engineer is still not in a position to be able to determine readily the high frequency resistance of a given wire or coil with any degree of certainty that his solution is accurate. Innumerable formulae exist for special cases and the designer has to adapt them to suit his own practical case, if he requires some idea of the high frequency resistance of the coil he is designing.

Much has been said on the advisability or otherwise of the use of stranded wire to reduce resistance to high frequency currents. It now appears fairly certain that stranded wires are preferable at low frequencies, and that for any given case there will be a certain number of strands which will give the best result for a given wave-length. The mechanical disadvantages of stranded conductors, such as difficulty in making connections and broken strands, and also cost of manufacture have, however, to be taken into consideration.

A close study of the subject is beyond the scope of this book, but the papers referred to above will give valuable information to anyone interested, and one or two main points are treated briefly in this chapter.

The increased resistance of a solid conductor to high frequency currents above that to direct currents is due to the current penetrating only a little way below the surface of the conductor, and also to eddy currents set up by the alternating flux cutting the conductor.

In order to calculate the amount of energy absorbed, Professor Howe treats portions of the conductor as a transmission line, energy being supplied in a direction at right angles to the surface of the conductor. He shows that the high frequency resistance, R_f, of a solid round wire carrying a current of such a high frequency that the penetration is small is given by the formula :—

$$\frac{R_f}{R_o} = \pi r \sqrt{\left(\frac{f\mu}{10^9 \rho}\right)} + 0{\cdot}25,$$

*See G. W. O. Howe : *Journal I.E.E.*, Vol. 54, No. 258, April 1916. G. W. O. Howe : *Proceedings of the Royal Society*, 1917, Vol. 93 (A), p. 468. G. W. O. Howe : *Journal I.E.E.*, Vol. 58, p. 152, February 1920. S. Butterworth : *Philosophical Transactions*, 1922, Vol. 222 (A), p. 57. C. L. Fortescue : *Journal I.E.E.*, Vol. 61, p. 933, August 1923.

where R_o = direct current resistance, r = radius of wire, f = frequency, μ = permeability, and ρ = specific resistance.

For copper $\mu = 1$, and $\rho = 1{\cdot}7 \times 10^{-6}$ ohms per cm. cube;

hence:— $$\frac{R_f}{R_o} = 0{\cdot}038d\sqrt{f} + 0{\cdot}25$$

where d is the diameter of the wire. For values of $d\sqrt{f}$ less than 32 the penetration is too great for the formula to be correct.

If the conductor is composed of fine strands of insulated wire the skin effect is reduced, but eddy currents are set up in each strand due to the magnetic flux produced by the other strands. Howe shows that if the strands are arranged properly and take their proper share of the current the losses can be taken as the sum of (a) those due to the direct current resistance, and (b) those due to eddy current losses due to the main field of the inductance.

The total resistance of a coil per cm. length of conductor is approximately:—

$$\left\{1{\cdot}27\left(\frac{\rho}{nd_1^{\,2}}\right) + 17{\cdot}4\left(\frac{nd_1^{\,4}}{\rho\lambda^2}\right)\left(\frac{K^2N^2}{D^2}\right)\right\} \text{ ohms,}$$

where N = number of turns, D = overall diameter in cm., K = a constant depending on the form of the coil, n = number of strands, d_1 = diameter of individual strands in cm., λ = wavelength in metres, and ρ = specific resistance in ohms per centimetre cube. The first term $\left(\frac{1{\cdot}27\rho}{nd_1^{\,2}}\right)$ represents the direct current resistance.

Fortescue gives various values of K as shown in the following table where b = axial length of the coil, t = winding depth of coil.

$\frac{t}{D}$	$\frac{b}{D} = 0{\cdot}5$	$\frac{b}{D} = 0{\cdot}75$	$\frac{b}{D} = 1{\cdot}0$	$\frac{b}{D} = 1{\cdot}25$	$\frac{b}{D} = 1{\cdot}5$
0·0	0·99	0·68	0·52	0·43	0·37
0·1	0·77	0·55	0·44	0·37	0·31
0·2	0·65	0·48	0·38	0·32	0·27
0·3	0·57	0·42	0·33	0·28	0·24
0·4	0·52	0·37	0·29	0·24	0·21

For solid conductors the total resistance per cm. of conductor is approximately

$$\left\{\frac{1\cdot094}{d_2}\sqrt{\left(\frac{\rho}{\lambda}\right)} + 13\cdot7d_2\sqrt{\left(\frac{\rho}{\lambda}\right)} \cdot \frac{K^2N^2}{D^2}\right\}\text{ohms}$$

where d_2 = diameter of conductor in cm.

173. Measurement of High Frequency Resistance of Wires and Coils.—The accurate measurement of the high frequency resistance of wires and coils is by no means a simple matter. Bridge methods are not satisfactory, and the most satisfactory method appears to be to measure the heat dissipated.

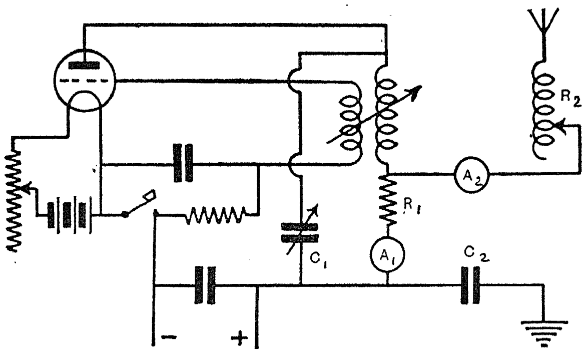


Fig. 194.

In the method described by Howe* the temperature rise of the coil was determined by means of a thermo-junction soldered to the centre of the coil. The deflection produced on a galvanometer by known values of high-frequency current and direct current when steady temperatures were reached enabled the high-frequency resistance to be determined.

A method described by Murphy in the discussion on Howe's paper is a simple method of determining fairly accurately the resistance of an aerial. Fig. 194 shows the arrangement used. A non-reactive resistance R_1, and a hot-

* G. W. O. Howe: *Journal I.E.E.*, Vol. 58, p. 152, February 1920.

wire ammeter A_1 are included in the anode circuit of an oscillating valve. The resistance R_2 to be measured is connected across them through an ammeter A_2 and in series with an air condenser C_2. The anode circuit is then tuned to the frequency of this circuit by condenser C_1. As the oscillatory circuit under test is as a whole non-reactive, the current in A_2 multiplied by the resistance R_2 of the circuit is equal to the voltage across A_1 and R_1. Hence R_2 can be determined fairly accurately. This method is not sufficiently accurate for calibration purposes as too many errors are possible, but it is simple and sufficiently accurate for most purposes.

174. Measurement of Decrement.—The usual method of determining the decrement of an oscillatory circuit is from the resonance curve. The curve may be plotted in various ways, *e.g.* as current squared against frequency or against the ratio of capacity required for resonance to the capacity in the circuit, or against the ratio of frequency squared to resonant frequency squared.

A wavemeter, with an accurate instrument for measuring current, is loosely coupled to the circuit whose decrement is to be measured, and the wavemeter current is measured for various values of capacity on each side of the resonance value. A small change in the value of the capacity in the wavemeter circuit should have no effect on the E.M.F. induced in the circuit by the oscillatory circuit under consideration, and the decrement of the wavemeter circuit should preferably be negligible, but at any rate it must be small and of known value.

If R = the effective resistance of the two circuits,
L = wavemeter inductance,
C = wavemeter capacity,
$\omega = 2\pi$ times the frequency of the oscillations in the main circuit,
E = E.M.F. induced in wavemeter circuit,
I = current in wavemeter circuit

then:—

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}.$$

If $\omega L = \frac{1}{\omega C}$, $I_r = \frac{E}{R}$, and resonance occurs. Let the value of C for resonance be C_r; then $C_r = \frac{1}{\omega^2 L}$. If C be increased slightly to some value C_1, the resonant frequency of the wavemeter circuit will be decreased to f_1, where $f_1 = \frac{\omega_1}{2\pi}$: hence:—

$$\frac{\omega_1}{\omega} = \sqrt{\frac{C_r}{C_1}}.$$

The value of the current will fall to I_1, where

$$I_1 = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C_1}\right)^2}} = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{\omega_1^2 L}{\omega}\right)^2}};$$

hence:— $$\frac{I_1^2}{I_r^2} = \frac{R^2}{R^2 + \left(\frac{\omega^2 - \omega_1^2}{\omega}\right)^2 L^2},$$

i.e. $$\sqrt{\frac{I_1^2}{I_r^2 - I_1^2}} = \frac{R}{\frac{\omega^2 - \omega_1^2}{\omega} L} = \frac{R}{\omega L} \times \frac{\omega^2}{\omega^2 - \omega_1^2}.$$

Now the logarithmic decrement of the combined circuits, or that of the circuit under consideration if the logarithmic decrement of the wavemeter is negligible, is equal to $\frac{\pi R}{\omega L} = \delta$, say.

$$\therefore \delta = \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}} \times \pi . \frac{\omega^2 - \omega_1^2}{\omega^2}$$

$$= \pi\left(1 - \frac{\omega_1^2}{\omega^2}\right)\sqrt{\frac{I_1^2}{I_r^2 - I_1^2}} = \pi\left(1 - \frac{C_r}{C_1}\right)\sqrt{\frac{I_1^2}{I_r^2 - I_1^2}};$$

hence δ can be determined.

If the logarithmic decrement of the wavemeter circuit is equal to δ_1, and the logarithmic decrement of the main circuit is δ_2, then $\delta = \delta_1 + \delta_2$.

If the capacity be decreased from C_r to C_2, then similarly :—

$$\delta = \pi\left(\frac{\omega_2^2}{\omega^2} - 1\right)\sqrt{\frac{I_2^2}{I_r^2 - I_2^2}}.$$

By taking suitable values of C_1 and C_2, I_1 and I_2 can be made equal, then by adding the two values of δ we get :—

$$2\delta = \pi\left(\frac{C_r}{C_2} - \frac{C_r}{C_1}\right)\sqrt{\frac{I^2}{I_r^2 - I^2}},$$

where $I = I_1 = I_2$..

If the resonance curve be plotted as square of current against ratio of resonant capacity to capacity, then $\frac{C_r}{C_2} - \frac{C_r}{C_1} =$ width of resonance curve for I_1^2; hence :—

$$\delta = \frac{\pi}{2}\sqrt{\frac{I^2}{I_r^2 - I^2}} \times \text{width of curve (Fig. 195).}$$

If $I^2 = 0{\cdot}5 I_r^2$, then :—

$$\delta = \frac{\pi}{2} \times \text{width of curve at half-height.}$$

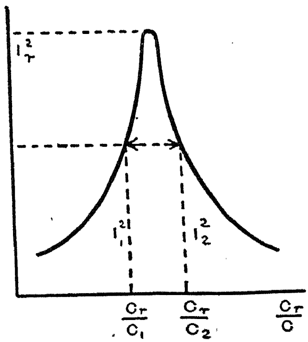


Fig. 195.

Similarly :—

$$\delta = \frac{\pi}{2}\left(\frac{f_2 + f_1}{f_r}\right)\left(\frac{f_2 - f_1}{f_r}\right)\sqrt{\frac{I^2}{I_r^2 - I^2}}.$$

Now $\frac{f_2 + f_1}{f_r} = 2$ if f_1 and f_2 are almost equal to f_r.

$$\therefore\ \delta = \pi\,\frac{(f_2 - f_1)}{f_r}\sqrt{\frac{I^2}{I_r^2 - I^2}}$$

$$= \pi\sqrt{\frac{I^2}{I_r^2 - I^2}} \times \text{width of curve (approximately),}$$

if the curve is plotted to a base of $\frac{f}{f_r}$.

175. Measurement of Coupling.—It is shown in Chaps., I., XIII. that the two frequencies f_1 and f_2 produced in two coupled circuits tuned to the same frequency are given by the formulae:—

$$f_1 = f_0 \times \frac{1}{\sqrt{1-k}} \quad \text{and} \quad f_2 = f_0 \times \frac{1}{\sqrt{1+k}},$$

where $f_0 =$ the natural frequency, and $k =$ the coefficient of coupling; or:—

$$k = \frac{\omega_1^2 - \omega_2^2}{\omega_1^2 + \omega_2^2},$$

where $\omega_1 = 2\pi f_1$, and $\omega_2 = 2\pi f_2$.

By means of a wavemeter ω_1 and ω_2 can be found, but if the wavemeter inductance is kept constant, and C_1 and C_2 are the corresponding values of the capacity, then

$$k = \frac{C_1 - C_2}{C_1 + C_2}.$$

176.—Measurement of Signal Strength.—The necessity for some standard method of measuring the strength of signals is remarked upon in Chapter XI. Various methods have been used employing telephones or galvanometers and comparing the incoming signal with local oscillations of known value.

A method used at the National Physical Laboratory has been described by Hollingworth.* In this method a multi-valve resistance-capacity amplifier is connected to the tuned receiving circuit. A galvanometer is connected in the anode lead of the last valve and balanced to read zero when normal anode current is passing. For this purpose a 2-volt cell and an adjustable resistance are connected across the galvanometer. An incoming signal reduces the anode current and the amount of reduction is indicated by the galvanometer.

The arrangement so far described has been used by many people, but the method of calibration employed at the N.P.L.

* J. Hollingworth on "The Measurement of the Electric Intensity of Received Radio Signals," *Journal I.E.E.*, Vol. 61, p. 501, April 1923.

is the special feature of their method. In this system calibration is carried out by disconnecting the receiving circuit from the amplifier and connecting the latter through a calibrated untuned coupling coil to a special local oscillator. The oscillator is then adjusted to give the same deflection as the signal. The untuned circuit and the design of the oscillator are the special features of the N.P.L. system, and special attention is paid to small details. The actual potential gradient of the electric field is calculated from the results obtained and the known dimensions of the aerial.

The Moullin voltmeter has also been used to measure the strength of signals and the amplification produced by valve amplifiers. Signal E.M.F.'s of about 300μV at 3×10^5 cycles have been accurately measured by interposing a two stage amplifier without using retro-action in the aerial, and signal E.M.F.'s of less than 50μV have been detected.*

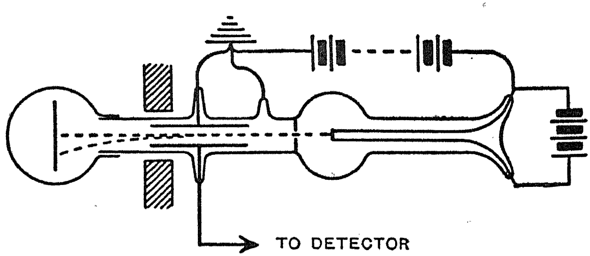


Fig. 196.

177. Cathode Ray Oscillograph.—An instrument which is used for many high frequency measurements is the cathode ray oscillograph, the principle of which is indicated in Fig. 196.

A stream of electrons emitted by a tungsten filament in an evacuated globe passes through a pinhole in a copper anode between which and the filament is a difference of potential of several thousand volts. The fine cathode ray produced passes between two long metal plates and the

* See E. B. Moullin: *Journal I.E.E.*, Vol. 61, p. 295, Feb. 1923, and Vol. 61, p. 67, Dec. 1922.

laminated poles of an electromagnet to the phosphorescent plate of a camera, where it produces a bright spot. The electromagnet is excited by alternating current which causes the spot to move with simple harmonic motion in a direction perpendicular to the magnet field. If a small oscillating P.D. is applied between the two metal plates the spot of light moves in a direction at right angles to the former direction. If a photographic plate replaces the phosphorescent plate an oscillogram can be obtained showing the wave form of the applied oscillatory P.D. By applying known P.D.'s to the plates the instrument can be calibrated and used to measure absolute values.

CHAPTER XIII.

A FEW MATHEMATICAL INVESTIGATIONS.

178. Introduction.—In this chapter, proofs of certain formulae merely quoted in preceding pages, and mathematical investigations of certain points in the theory of wireless telegraphy and telephony which have been simply summarised or referred to, are set out in detail.

As already indicated, readers with the necessary mathematical knowledge should carefully study the various sections of this chapter concurrently with the corresponding sections as they arise in the text. Other readers are strongly advised to endeavour to understand in a general way the main steps whereby the final conclusions are reached, even although they may not be familiar with the actual solutions of differential equations. At the same time we would emphasise that students of Physics, whether pure or applied, cannot realise too early that a knowledge of the rudiments of the differential and integral calculus and the methods of solution of the simpler differential equations is an essential part of their mental equipment: the necessary knowledge can be acquired by a slight expenditure of time.

179. Alternating Current in a Circuit with Resistance and Inductance. (See Art. 1.)—Perhaps the simplest method of investigation is to suppose an alternating current (sine curve) exists in a circuit, and to find what must be the nature of the E.M.F. in the circuit in order to produce such a current.

It is well known that in the case of a coil of wire rotating in a magnetic field, the alternating current (I) produced at any instant may be expressed by the relation :—

$$\mathrm{I} = \mathrm{I}_0 \sin \omega t,$$

where $t =$ time elapsed since the fixed zero of time, $\omega =$ angular velocity $= 2\pi f$ (where $f =$ frequency) and $\mathrm{I}_0 =$ the maximum value of the current.

Let then the alternating current in the circuit be denoted by:—

$$I = I_0 \sin \omega t,$$

$$\therefore \frac{dI}{dt} = I_0 \omega \cos \omega t,$$

$\therefore$ Induced E.M.F. (self induction) $= L \dfrac{dI}{dt} = LI_0 \omega \cos \omega t$,

where $L =$ coefficient of self induction. Now, by applying Ohm's law to the circuit, we get:—

$$E = IR + L\frac{dI}{dt}.$$

$$\therefore E = I_0 R \sin \omega t + LI_0 \omega \cos \omega t,$$

i.e.

$$E = I_0 [R \sin \omega t + L\omega \cos \omega t].$$

This may be written

$$E = I_0 \sqrt{R^2 + L^2\omega^2} \sin (\omega t + \phi),$$

if

$$\frac{R}{\sqrt{R^2 + L^2\omega^2}} = \cos \phi \quad \text{and} \quad \frac{L\omega}{\sqrt{R^2 + L^2\omega^2}} = \sin \phi,$$

that is, if

$$\tan \phi = \frac{L\omega}{R} = \frac{2\pi f L}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Here the maximum value of E is $I_0 \sqrt{R^2 + L^2\omega^2}$, and if this be denoted by E_0 we have

$$E = E_0 \sin (\omega t + \phi).$$

Hence when the current varies harmonically in a circuit the electromotive force in the circuit also varies harmonically, with the same frequency, and the maximum value of the electromotive force is $\sqrt{R^2 + L^2\omega^2}$ times the maximum value of the current. The phase of the electromotive force is, however, in advance of that of the current, or *the phase of the current lags behind that of the electromotive force by $\phi/2\pi$ of a complete period, the angle of lag ϕ being such that tan* $\phi = L\omega/R$, where R is the resistance, L the self-inductance of the circuit, and $\omega/2\pi$ the frequency (f) of the alternations of the current and the electromotive force in the circuit.

Hence, if the electromotive force in the circuit be given by

$$E = E_0 \sin \omega t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

then for the current we have, from the above,

$$I = I_0 (\sin \omega t - \phi) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

i.e.
$$I = \frac{E_0}{\sqrt{R^2 + L^2\omega^2}} \sin (\omega t - \phi) \quad \ldots\ldots\ldots \quad (4)$$

since I_0, the maximum current, is given by

$$I_0 = \frac{E_0}{\sqrt{R^2 + L^2\omega^2}} = \frac{E_0}{\sqrt{R^2 + 4\pi^2 f^2 L^2}} \quad \ldots\ldots\ldots \quad (5)$$

The quantity $\sqrt{R^2 + L^2\omega^2}$ is called the **impedance** of the circuit, and the quantity $L\omega$ is called the **reactance** of the circuit. It should be noted that the impedance includes both the ohmic resistance and the reactance.

Clearly if E and I be virtual values, then since $E = \cdot 707 E_0$ and $I = \cdot 707 I_0$, we have, as stated in Chapter I.,

$$I \text{ (virtual amperes)} = \frac{E \text{ (virtual volts)}}{\sqrt{R^2 + L^2\omega^2}}.$$

The reader may prefer the following treatment to the preceding:—

In a circuit containing inductance and resistance, if E follows the simple harmonic law, $E = E_0 \sin \omega t$:—

$$IR + L\frac{dI}{dt} = E_0 \sin \omega t.$$

Now assume as a trial solution that

$$I = Z \sin (\omega t - \phi),$$

where Z and ϕ are to be determined. Substituting:—

$$ZR \sin (\omega t - \phi) + ZL\omega \cos (\omega t - \phi) = E_0 \sin \omega t \ldots (6)$$

$$\therefore ZR (\sin \omega t \,.\, \cos \phi - \cos \omega t \,.\, \sin \phi)$$
$$+ ZL\omega (\cos \omega t \,.\, \cos \phi + \sin \omega t \,.\, \sin \phi) = E_0 \sin \omega t,$$

i.e. $(ZR \cos \phi \,.\, \sin \omega t + ZL\omega \sin \phi \,.\, \sin \omega t)$
$$- (ZR \sin \phi \cos \omega t - ZL\omega \cos \phi \,.\, \cos \omega t) = E_0 \sin \omega t.$$

Hence, equating coefficients:—

$$ZR \cos \phi + ZL\omega \sin \phi = E_0 \quad \ldots\ldots\ldots\ldots \quad (7)$$

$$- ZR \sin \phi + ZL\omega \cos \phi = 0 \quad \ldots\ldots\ldots\ldots \quad (8)$$

Squaring and adding :—

$$Z^2R^2 + Z^2L^2\omega^2 = E_0^2, \quad i.e.\ Z^2(R^2 + L^2\omega^2) = E_0^2,$$

$$\therefore Z = \frac{E_0}{\sqrt{R^2 + L^2\omega^2}},$$

and
$$I = \frac{E_0}{\sqrt{R^2 + L^2\omega^2}} \sin(\omega t - \phi) \quad \ldots\ldots\ldots\ldots (9)$$

From (8)

$$\tan\phi = \frac{L\omega}{R} = \frac{2\pi f L}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Further
$$I_0 = \frac{E_0}{\sqrt{R^2 + L^2\omega^2}} = \frac{E_0}{\sqrt{R^2 + 4\pi^2 f^2 L^2}} \quad \ldots\ldots (11)$$

180. Alternating Current in a Circuit with Resistance, Inductance, and Capacity. (See Art. 1.)—When a harmonically varying electromotive force $E_0 \sin \omega t$ is applied to a circuit containing a resistance R with inductance L, and a capacity C in series, we have

$$IR + L\frac{dI}{dt} + V = E_0 \sin \omega t \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where I is the current and V the potential difference on the condenser. If Q be the charge on the condenser at any instant $V = Q/C$, and we get

$$IR + L\frac{dI}{dt} + \frac{Q}{C} = E_0 \sin \omega t \ldots\ldots\ldots\ldots\ldots (2)$$

Now, as in Art. 179, let $I = Z \sin(\omega t - \phi)$,

i.e.
$$\frac{dQ}{dt} = Z \sin(\omega t - \phi),$$

$$\therefore Q = -\frac{Z}{\omega} \cos(\omega t - \phi).$$

Substituting in the equation above :—

$$ZR \sin(\omega t - \phi) + LZ\omega \cos(\omega t - \phi) - \frac{Z}{C\omega} \cos(\omega t - \phi)$$
$$= E_0 \sin \omega t,$$

$$\therefore ZR \sin(\omega t - \phi) + \left(L\omega - \frac{1}{C\omega}\right) Z \cos(\omega t - \phi) = E_0 \sin \omega t.$$

This is identical with equation (6) of Art. 179, except that

in place of $L\omega$ we have $\left(L\omega - \frac{1}{C\omega}\right)$; as in that section the solution is:—

$$Z = \frac{E_0}{\sqrt{R^2 + \left(L\omega - \frac{1}{C\omega}\right)^2}}$$

$$I = \frac{E_0}{\sqrt{R^2 + \left(L\omega - \frac{1}{C\omega}\right)^2}} \sin(\omega t - \phi) \quad \ldots(3)$$

$$\tan\phi = \frac{L\omega - \frac{1}{C\omega}}{R} = \frac{2\pi f L - \frac{1}{2\pi f C}}{R} \quad \ldots\ldots\ldots\ldots(4)$$

$$I_0 = \frac{E_0}{\sqrt{R^2 + \left(L\omega - \frac{1}{C\omega}\right)^2}} = \frac{E_0}{\sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2}} \quad \ldots(5)$$

and clearly, if $L\omega = 1/C\omega$, *i.e.* if $2\pi f L = 1/2\pi f C$, capacity and inductance neutralise, the angle ϕ is $0°$, and

$$I = \frac{E_0 \sin \omega t}{R}, \qquad I_0 = \frac{E_0}{R}.$$

Thus the current and the applied electromotive force are in the same phase, and the current has the same value as in a circuit of resistance R free from inductance and capacity. If $L\omega > 1/C\omega$ the current *lags*, if $L\omega < 1/C\omega$ the current *leads*.

The condition for the neutralisation of the inductance effect by the capacity effect may be obtained without working out the general solution above. From (1) capacity and inductance neutralise if $L\frac{dI}{dt} = -V$. Now V will be a harmonically varying quantity with the same period as the electromotive force, and may be written $V = V_0 \sin(\omega t - \phi)$. Further, $I = dQ/dt = d(CV)/dt = C \, . \, dV/dt$; hence $I = C\omega V_0 \cos(\omega t - \phi)$ and $dI/dt = -C\omega^2 V_0 \sin(\omega t - \phi)$. Thus the required condition $L \, . \, dI/dt = -V$ becomes

$$LC\omega^2 V_0 \sin(\omega t - \phi) = V_0 \sin(\omega t - \phi),$$

i.e.

$$LC = \frac{1}{\omega^2},$$

$$\therefore L\omega = \frac{1}{C\omega}, \quad \text{or} \quad 2\pi f L = \frac{1}{2\pi f C},$$

as shown above.

Further, since $\omega = 2\pi/T$, where T is the period of the applied electromotive force, we have

$$LC = \frac{T^2}{4\pi^2}, \textit{ i.e. } T = 2\pi\sqrt{LC}.$$

This, as shown in Chapter I., is the period for electrical oscillations in the circuit; hence *when the period of the applied electromotive force is the same as that of the circuit for electric oscillations the effect of capacity neutralises the effect of inductance.*

If the circuit possesses capacity and resistance *but no inductance,* it may be shown that the law becomes :—

$$I_0 = \frac{E_0}{\sqrt{R^2 + \frac{1}{C^2\omega^2}}} = \frac{E_0}{\sqrt{R^2 + \frac{1}{4\pi^2 f^2 C^2}}} \quad \ldots\ldots\ldots (6)$$

The effect of capacity alone is to make the current *lead* in front of the pressure, and

$$\text{tan angle of lead} = \frac{1}{2\pi f CR} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

The student should prove these statements.

Clearly, if in a circuit containing capacity, resistance and inductance, $2\pi f L = 1/2\pi f C$, then $2\pi f L/R = 1/2\pi f CR$, *i.e.* the lag due to inductance is equal to the lead due to capacity, and the two neutralise as already proved.

The two preceding sections (Arts. 179, 180) are reproduced from *Advanced Text-book of Magnetism and Electricity* by R. W. Hutchinson, M.Sc., A.M.I.E.E. (University Tutorial Press).

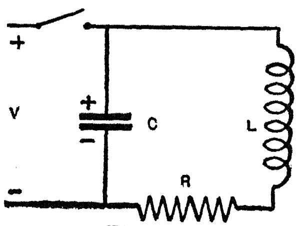


Fig. 197.

181. Theory of the Discharge of a Condenser. (See Art. 10.)—The conditions necessary for the production and maintenance of an oscillatory current are apparent when the discharge of a condenser is treated mathematically.

Fig. 197 represents a circuit containing a condenser, an inductance, and a resistance, the condenser being charged by

the supply and then allowed to discharge through the inductance and resistance.

Let $V =$ the voltage across the condenser when charged,
$Q =$ the charge on the condenser when the voltage is V.

Then $$C = \frac{Q}{V} \quad \text{and} \quad Q = CV.$$

Let $i =$ the instantaneous value of the current at a time t after the condenser begins to discharge,
$q =$ the charge on the condenser at a time t,
$v =$ the P.D. across the condenser at a time t.

Then $$q = Cv, \text{ and } i = -\frac{dq}{dt} = -C\frac{dv}{dt}.$$

Also $$v = iR + L\frac{di}{dt}.$$

$$\therefore \quad v - L\frac{di}{dt} - iR = 0.$$

i.e. $$v + LC\frac{d^2v}{dt^2} + CR\frac{dv}{dt} = 0.$$

$$\therefore \quad \frac{d^2v}{dt^2} + \frac{R}{L}\cdot\frac{dv}{dt} + \frac{1}{LC}\cdot v = 0 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

The solution of this equation is of the form:—

$$v = Me^{m_1t} + Ne^{m_2t},$$

where M and N depend on the original conditions, and m_1 and m_2 are roots of the equation:—

$$\lambda^2 + \frac{R}{L}\lambda + \frac{1}{LC} = 0$$

$$\therefore \; m_1 = -\frac{R}{2L} + \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \quad \ldots\ldots\ldots\ldots (2)$$

and $$m_2 = -\frac{R}{2L} - \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \quad \ldots\ldots\ldots\ldots (3)$$

m_1 and m_2 are real if CR^2 is greater than 4L.
m_1 and m_2 are imaginary if CR^2 is less than 4L.
m_1 and m_2 are equal if CR^2 is equal to 4L.

Consider the conditions when $t = 0$: then:—

$$e^{m_1t} = e^{m_2t} = 1 \quad \text{and } v = V = \frac{Q}{C}.$$

$$\therefore \; V = M + N.$$

Also, when $t=0$, $i=0$,

$$\therefore \frac{dv}{dt}=0, \text{ since } i=-\mathrm{C}\frac{dv}{dt}.$$

Now
$$\frac{dv}{dt}=\mathrm{M}m_1e^{m_1t}+\mathrm{N}m_2e^{m_2t}.$$

$$\therefore 0=\mathrm{M}m_1+\mathrm{N}m_2.$$

Also
$$\mathrm{V}=\mathrm{M}+\mathrm{N},$$

hence :— $\mathrm{M}=\mathrm{V}\dfrac{m_2}{m_2-m_1}$ and $\mathrm{N}=\mathrm{V}\dfrac{m_1}{m_1-m_2}$.

$$\therefore v=\mathrm{V}\left(\frac{m_2}{m_2-m_1}\cdot e^{m_1t}-\frac{m_1}{m_2-m_1}\cdot e^{m_2t}\right) \ldots\ldots (4)$$

and
$$i=-\mathrm{C}\frac{dv}{dt}$$

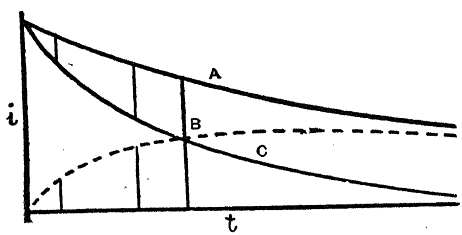
$$=-\mathrm{Q}\cdot\frac{m_1m_2}{m_2-m_1}\left(e^{m_1t}-e^{m_2t}\right)$$

$$=\frac{\mathrm{V}}{\sqrt{\mathrm{R}^2-\frac{4\mathrm{L}}{\mathrm{C}}}}\left(e^{m_1t}-e^{m_2t}\right) \ldots\ldots\ldots\ldots\ldots (5)$$

which is real if m_1 and m_2 are real, *i. e.* if CR^2 is greater than $4\mathrm{L}$.

When $t=0$, $i=0$; and when $t=\infty$, $i=0$; therefore there is a maximum value of i between these values of t: i is the difference between two exponential curves, and is shown in Fig. 198. The value of the current, therefore, rises to a maximum and then dies away to zero, *and is unidirectional.*

The maximum value of the current is given when $\dfrac{di}{dt}=0$.



(A) $i=\dfrac{\mathrm{V}}{\sqrt{\mathrm{R}^2-\frac{4\mathrm{L}}{\mathrm{C}}}}e^{m_1t}$. (C) $i=\dfrac{\mathrm{V}}{\sqrt{\mathrm{R}^2-\frac{4\mathrm{L}}{\mathrm{C}}}}e^{m_2t}$.

(B) $i=\dfrac{\mathrm{V}}{\sqrt{\mathrm{R}^2-\frac{4\mathrm{L}}{\mathrm{C}}}}\left(e^{m_1t}-e^{m_2t}\right)$.

Fig. 198.

i.e.
$$\frac{di}{dt} = \frac{V}{\sqrt{R^2 - \frac{4L}{C}}}\left(m_1 e^{m_1 t} - m_2 e^{m_2 t}\right) = 0$$

$$\therefore\ m_1 e^{m_1 t} = m_2 e^{m_2 t} \qquad \therefore\ \frac{m_1}{m_2} = e^{(m_2 - m_1)t}$$

$$\therefore\ t = \frac{\log_e m_1 - \log_e m_2}{m_2 - m_1}$$

$$\therefore\ i_{\text{max.}} = \frac{V}{\sqrt{R^2 - \frac{4L}{C}}}\left(\frac{m_2}{m_1} e^{m_2 t} - e^{m_2 t}\right)$$

$$= -Qe^{m_2 t} \, . \, m_2 = -Qe^{m_1 t} \, . \, m_1,$$

or
$$i_{\text{max.}} = Q\sqrt{m_1 m_2 e^{(m_1 + m_2)t}}$$

$$= \frac{Q}{\sqrt{LC}} . e^{-\frac{R}{2L}t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where t has the above value. For real values of i (and uni-directional discharge) CR^2 must be greater than $4L$.

The case when $CR^2 = 4L$ is a special case, and is not of practical importance. The solution is :—

$$i = \frac{V}{L} \cdot te^{-\frac{R}{2L} \cdot t} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and
$$v = Ve^{-\frac{R}{2L} \cdot t}\left(1 - \frac{R}{2L} \cdot t\right) \ldots\ldots\ldots\ldots (8)$$

Now consider the case when m_1 and m_2 are imaginary, *i.e.* $CR^2 < 4L$.

Let $m_1 = -\alpha + j\omega$ and $m_2 = -\alpha - j\omega$,

where $\alpha = \frac{R}{2L}$ and $\omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$ and $j = \sqrt{-1}$.

Then $$v = \mathrm{V}\left(\frac{m_2}{m_2 - m_1} . e^{m_1 t} - \frac{m_1}{m_2 - m_1} . e^{m_2 t}\right)$$

$$= \mathrm{V}e^{-at}\left(\frac{m_2}{m_2 - m_1} . e^{j\omega t} - \frac{m_1}{m_2 - m_1} . e^{-j\omega t}\right)$$

$$= \mathrm{V}e^{-at}\left(\frac{-\alpha - j\omega}{-2j\omega} . e^{j\omega t} - \frac{-\alpha + j\omega}{-2j\omega} . e^{-j\omega t}\right)$$

$$= \mathrm{V}e^{-at}\left(\frac{\alpha}{\omega} . \frac{e^{j\omega t} - e^{-j\omega t}}{2j} + \frac{e^{j\omega t} + e^{-j\omega t}}{2}\right)$$

$$= \mathrm{V}e^{-at}\left(\frac{\alpha}{\omega}\sin\omega t + \cos\omega t\right)$$

$$= \mathrm{V}e^{-at}\sqrt{1 + \frac{\alpha^2}{\omega^2}}\left\{\cos(\omega t - \phi)\right\} \quad \ldots\ldots\ldots (9)$$

where $\tan\phi = \dfrac{\alpha}{\omega}$.

Also $$i = -\mathrm{C}\frac{dv}{dt}$$

$$= \mathrm{CV}\left(\frac{\omega^2 + \alpha^2}{\omega}\right)e^{-at}\sin\omega t$$

$$= \omega\mathrm{CV}\left(1 + \frac{\alpha^2}{\omega^2}\right)e^{-at}\sin\omega t.$$

If $\dfrac{\alpha^2}{\omega^2}$ is negligible, which is usually the case:—

$$i = \omega\mathrm{CV}e^{-at}\sin\omega t \text{ (approximately)} \ldots\ldots\ldots (10)$$

Since $$\omega^2 = \frac{1}{\mathrm{LC}} - \frac{\mathrm{R}^2}{4\mathrm{L}^2} = \frac{1}{\mathrm{LC}} - \alpha^2$$

$$\mathrm{C} = \frac{1}{\mathrm{L}(\omega^2 + \alpha^2)}$$

$$\therefore i = \frac{\mathrm{V}}{\omega\mathrm{L}}e^{-at}\sin\omega t \text{ (accurately)} \ldots\ldots\ldots (11)$$

The last equation represents an oscillatory current whose frequency is $\dfrac{\omega}{2\pi}$, and whose amplitude is equal to $\dfrac{\mathrm{V}}{\omega\mathrm{L}} . e^{-at}$ and therefore decreases as the time increases; *i.e.* the oscillations are damped.

The frequency $\frac{\omega}{2\pi}$ of the oscillations is called the natural frequency of the circuit, and is equal to $\frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}$.

The term $\frac{R^2}{4L^2}=a^2$ determines the damping, and is therefore kept small if the losses are to be kept small, and can usually be neglected compared with $\frac{1}{LC}$. The frequency of the oscillation is, therefore, equal to $\frac{1}{2\pi\sqrt{LC}}$ for all practical purposes, and this value is called the resonant frequency of the circuit. The resonant frequency is, therefore, equal to the natural frequency when the damping is negligible.

182. Theory of Coupled Oscillatory Circuits. (See Art. 16.)—Let i_1 and i_2 be the instantaneous values of the currents in the primary and secondary circuits shown in Fig. 199, and let v_1 and v_2 be the instantaneous values of the P.D. between the plates of the condensers.

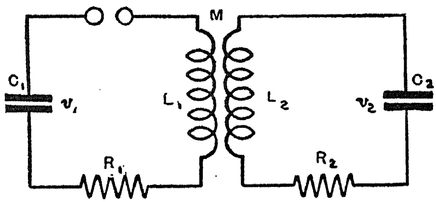


Fig. 199.

Then $$v_1 = L_1\frac{di_1}{dt} + M\frac{di_2}{dt} + i_1R_1$$

and $$v_2 = L_2\frac{di_2}{dt} + M\frac{di_1}{dt} + i_2R_2.$$

Differentiate the first equation, and put $i_1 = -C_1\frac{dv_1}{dt}$.

Then $$L_1\frac{d^2i_1}{dt^2} + M\frac{d^2i_2}{dt^2} + R_1\frac{di_1}{dt} + \frac{i_1}{C_1} = 0.$$

Similarly, $$L_2\frac{d^2i_2}{dt^2} + M\frac{d^2i_1}{dt^2} + R_2\frac{di_2}{dt} + \frac{i_2}{C_2} = 0.$$

Differentiating twice gives :—

$$L_1 \frac{d^4 i_1}{dt^4} + M \frac{d^4 i_2}{dt^4} + R_1 \frac{d^3 i_1}{dt^3} + \frac{d^2 i_1}{dt^2} \cdot \frac{1}{C_1} = 0$$

and
$$L_2 \frac{d^4 i_2}{dt^4} + M \frac{d^4 i_1}{dt^4} + R_2 \frac{d^3 i_2}{dt^3} + \frac{d^2 i_2}{dt^2} \cdot \frac{1}{C_2} = 0.$$

Substituting for $\frac{d^2 i_2}{dt^2}$ and $\frac{d^3 i_2}{dt^3}$ and $\frac{d^4 i_2}{dt^4}$ in terms of i_1, and multiplying by $-\frac{M}{L_1 L_2}$ we get :—

$$\left(1 - \frac{M^2}{L_1 L_2}\right) \frac{d^4 i_1}{dt^4} + \left(\frac{R_1}{L_1} + \frac{R_2}{L_2}\right) \frac{d^3 i_1}{dt^3} + \left(\frac{1}{L_1 C_1} + \frac{1}{L_2 C_2} + \frac{R_1 R_2}{L_1 L_2}\right) \frac{d^2 i_1}{dt^2} + \left(\frac{R_2}{L_1 L_2 C_1} + \frac{R_1}{L_1 L_2 C_2}\right) \frac{d i_1}{dt} + \left(\frac{1}{L_1 L_2 C_1 C_2}\right) i_1 = 0.$$

A similar equation can be found in terms of i_2.

Substituting $k = \frac{M}{\sqrt{L_1 L_2}}$, $\alpha_1 = \frac{R_1}{2L_1}$, $\alpha_2 = \frac{R_2}{2L_2}$, $\frac{1}{\sqrt{L_1 C_1}} = \omega_{01}$, and $\frac{1}{\sqrt{L_2 C_2}} = \omega_{02}$, we get :—

$$(1 - k^2) \frac{d^4 i_1}{dt^4} + 2(\alpha_1 + \alpha_2) \frac{d^3 i_1}{dt^3} + (\omega_{01}{}^2 + \omega_{02}{}^2 + 4\alpha_1 \alpha_2) \frac{d^2 i_1}{dt^2} + 2(\alpha_2 \omega_{01}{}^2 + \alpha_1 \omega_{02}{}^2) \frac{di}{dt} + \omega_{01}{}^2 \omega_{02}{}^2 i_1 = 0.$$

A solution of this equation is $i_1 = Ae^{mt}$, where m is given by the equation :—

$$(m^2 + 2\alpha_1 m + \omega_{01}{}^2)(m^2 + 2\alpha_2 m + \omega_{02}{}^2) = k^2 m^4.$$

Let $m = -\alpha' \pm j\omega_1$ and $-\alpha'' \pm j\omega_2$, where $j = \sqrt{-1}$: then :—

$$i_1 = A_1 e^{(-\alpha' + j\omega_1)t} + A_2 e^{(-\alpha' - j\omega_1)t} + A_3 e^{(-\alpha'' + j\omega_2)t} + A_4 e^{(-\alpha'' - j\omega_2)t}$$

$$= e^{-\alpha' t}(A_1 e^{j\omega_1 t} + A_2 e^{-j\omega_1 t}) + e^{-\alpha'' t}(A_3 e^{j\omega_2 t} + A_4 e^{-j\omega_2 t})$$

$$= A_1' e^{-\alpha' t} \cos(\omega_1 t - \phi_1') + A_1'' e^{-\alpha'' t} \cos(\omega_2 t - \phi_1'').$$

Similarly :—

$i_2 = A_2'e^{-\alpha' t} \cos(\omega_1 t - \phi_2') + A_2''e^{-\alpha'' t} \cos(\omega_2 t - \phi_2'')$.

These solutions show that there are two oscillations of different frequencies present in the secondary circuit, and also in the primary, as described on page 27.

If the damping is negligible, which is usually the case in oscillatory circuits used in wireless telegraphy, then $\alpha_1 = \alpha_2 = 0$.

The equation in m then becomes :—

$$(m^2 + \omega_{01}^2)(m^2 + \omega_{02}^2) = k^2 m^4,$$

or

$$m^4 + \frac{(\omega_{01}^2 + \omega_{02}^2)m^2}{1 - k^2} + \frac{\omega_{01}^2\omega_{02}^2}{1 - k^2} = 0,$$

and the roots become $\pm j\omega_1$ and $\pm j\omega_2$.

$$\therefore\ (m + j\omega_1)(m - j\omega_1)(m + j\omega_2)(m - j\omega_2) = 0.$$

$$\therefore\ m^4 + (\omega_1^2 + \omega_2^2)m^2 + \omega_1^2\omega_2^2 = 0.$$

Hence

$$\omega_1^2 + \omega_2^2 = \frac{\omega_{01}^2 + \omega_{02}^2}{1 - k^2},$$

and

$$\omega_1^2\omega_2^2 = \frac{\omega_{01}^2\,\omega_{02}^2}{1 - k^2}.$$

$$\therefore\ \omega_1^2 = \frac{\omega_{01}^2 + \omega_{02}^2 + \sqrt{(\omega_{01}^2 - \omega_{02}^2)^2 + 4\omega_{01}^2\omega_{02}^2k^2}}{2(1 - k^2)},$$

and

$$\omega_2^2 = \frac{\omega_{01}^2 + \omega_{02}^2 - \sqrt{(\omega_{01}^2 - \omega_{02}^2)^2 + 4\omega_{01}^2\omega_{02}^2k^2}}{2(1 - k^2)}.$$

If the two circuits are in tune, then $\omega_{01} = \omega_{02} = \omega_0 = 2\pi f_0$, where f_0 = the natural frequency of each circuit.

Then

$$\omega_1^2 = \omega_0^2\frac{(1 + k)}{(1 - k^2)} = \frac{\omega_0^2}{1 - k}.$$

$$\therefore\ \omega_1 = \frac{\omega_0}{\sqrt{1 - k}} \quad \text{and} \quad \omega_2 = \frac{\omega_0}{\sqrt{1 + k}},$$

or

$$k = \frac{\omega_1^2 - \omega_2^2}{\omega_1^2 + \omega_2^2}.$$

Hence

$$f_1 = \frac{f_0}{\sqrt{1 - k}} \quad \text{and} \quad f_2 = \frac{f_0}{\sqrt{1 + k}},$$

where f_1 and f_2 are the frequencies of the two sets of oscillations.

The above results have been arrived at on the assumption that the damping is negligible. If the logarithmic decrement of the secondary is less than about 0·2 the error is not greater than about 5 per cent.

The resultant effect of the two sets of oscillations is to produce an oscillation whose frequency is equal to $f_1 - f_2$. This can be shown by adding the instantaneous values of the two currents. From page 250, the instantaneous value of the resultant current is given by:—

$$i = \mathrm{A}\left\{e^{-\alpha' t}\cos(\omega_1 t - \phi_1) + e^{-\alpha'' t}\cos(\omega_2 t - \phi_2)\right\}$$

If the damping is negligible, then $\alpha' = \alpha'' = 0$.

$$\therefore\ i = \mathrm{A}\left\{\cos(\omega_1 t - \phi_1) + \cos(\omega_2 t - \phi_2)\right\}$$

$$= \mathrm{A}\left\{2\cos\left(\frac{\omega_1 t - \phi_1 - \omega_2 t + \phi_2}{2}\right) \times \cos\left(\frac{\omega_1 t - \phi_1 + \omega_2 t - \phi_2}{2}\right)\right\}$$

$$= 2\mathrm{A}\left\{\cos\frac{(\omega_1 - \omega_2)t - (\phi_1 - \phi_2)}{2} \times \cos\frac{(\omega_1 + \omega_2)t - (\phi_1 + \phi_2)}{2}\right\}$$

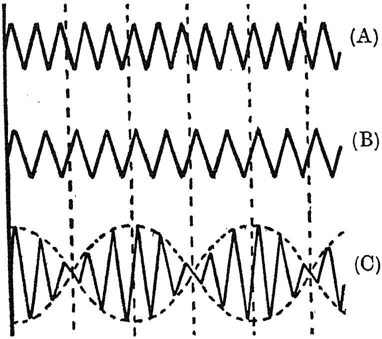
$$= 2\mathrm{A}\left[\cos\left\{\left(\frac{\omega_1 - \omega_2}{2}\right)t - \theta_1\right\} \times \cos\left\{\left(\frac{\omega_1 + \omega_2}{2}\right)t - \theta_2\right\}\right]$$

Now $\omega_1 = 2\pi f_1$, and $\omega_2 = 2\pi f_2$.

$$\therefore\ i = 2\mathrm{A}\left[\cos\left\{2\pi\left(\frac{f_1 - f_2}{2}\right)t - \theta_1\right\} \times \cos\left\{2\pi\left(\frac{f_1 + f_2}{2}\right)t - \theta_2\right\}\right].$$

This represents an oscillation whose amplitude is represented by $2\mathrm{A}\cos\left\{2\pi\left(\frac{f_1 - f_2}{2}\right)t - \theta_1\right\}$, and whose frequency is $\frac{(f_1 + f_2)}{2}$. The amplitude becomes a maximum every time $\cos\left\{2\pi\left(\frac{f_1 - f_2}{2}\right)t - \theta_1\right\} = 1$, which occurs $f_1 - f_2$ times a second. Hence the frequency of the complex oscillation is $f_1 - f_2$, since its maximum value occurs $f_1 - f_2$ times a second, but the frequency of individual oscillations composing the complex oscillation is $\frac{f_1 + f_2}{2}$, which is the mean of the frequencies of the two separate oscillations.

Fig. 200 represents the oscillations of frequencies f_1 and f_2 and their resultant.



(A) $i_1 = A \cos(2\pi f_1 t - \phi_1)$.
(B) $i_2 = A \cos(2\pi f_2 t - \phi_2)$.
(C) $i = i_1 + i_2$.
Fig. 200.

183. Transmission of Electromagnetic Waves along Wires. (See Art. 20.)—The actual nature of electromagnetic waves and their propagation can most easily be understood by considering the case of electromagnetic waves transmitted along wires.

Consider the transmission line shown in Fig. 201.

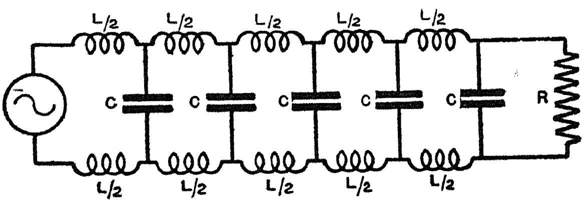


Fig. 201.

Let the capacity per unit length $= C$, the inductance per unit length $= L$, and assume the resistance and the leakage along the line to be negligible.

Consider a length of line dx at a distance x from the receiving end. Then the drop in voltage along the line for a distance dx is equal to $\left(\mathrm{L}\dfrac{di}{dt}\right)dx = dv$,

i.e.
$$\frac{dv}{dx} = \mathrm{L}\frac{di}{dt},$$

where i is the value of the current passing through the length dx at that instant. The drop in the value of the current along the length dx is $\left(\mathrm{C}\dfrac{dv}{dt}\right)dx$,

$$\therefore \frac{di}{dx} = \mathrm{C}\frac{dv}{dt}.$$

If $i = \mathrm{I}_{\max.} \sin \omega t$, then $\dfrac{di}{dt} = \mathrm{I}_{\max.}\, \omega \cos \omega t$ and $\dfrac{d^2i}{dt^2} = -\omega^2 i$.

$$\therefore \frac{d^2i}{dx^2} = -\omega^2 \mathrm{LC}i$$

and
$$\frac{d^2v}{dx^2} = -\omega^2 \mathrm{LC}v.$$

The solutions of these equations are:—

$$i = \mathrm{A} \cos \omega\sqrt{\mathrm{LC}}\,.\,x + \mathrm{B} \sin \omega\sqrt{\mathrm{LC}}\,.\,x.$$

$$v = \mathrm{A}' \cos \omega\sqrt{\mathrm{LC}}\,.\,x + \mathrm{B}' \sin \omega\sqrt{\mathrm{LC}}\,.\,x.$$

Let i_2 = current at receiving end, *i.e.* when $x = 0$, then $i_2 = \mathrm{A}$.

Similarly, if x be taken from sending end and i_1 = current at sending end, then $i_1 = \mathrm{B}$.

$$\therefore i = i_1 \sin \omega\sqrt{\mathrm{LC}}\,.\,x + i_2 \cos \omega\sqrt{\mathrm{LC}}\,.\,x.$$

Similarly:—

$$v = v_1 \sin \omega\sqrt{\mathrm{LC}}\,.\,x + v_2 \cos \omega\sqrt{\mathrm{LC}}\,.\,x.$$

These equations show that the current at any point is the sum of two currents, the value of one of these currents varying according to a sine law as x varies, and the other varying according to a cosine law. Thus the effect is that of a wave moving along the transmission line from the sending end, being reflected at the receiving end, and travelling back from there.

Similarly, there are two waves of voltage, each being in phase with its corresponding current wave.

At all points along the line for which $\omega\sqrt{LC}\,.\,x$ is equal to a multiple of 2π, the value of the current due to a wave is constant, therefore the distance between all these points is $\frac{2\pi}{\omega\sqrt{LC}}$. The distance between two points where the value of the current is always identical is called the wave-length of the wave, therefore the wave-length in this particular case is equal to $\frac{2\pi}{\omega\sqrt{LC}} = \lambda$.

The wave advances this distance in one cycle. Hence :—

$$\text{Velocity} = \text{Wave length} \times \text{Frequency},$$
$$= \frac{2\pi}{\omega\sqrt{LC}} \times f = \frac{2\pi}{\omega\sqrt{LC}} \times \frac{\omega}{2\pi},$$
$$= \frac{1}{\sqrt{LC}},$$

and therefore the velocity is constant whatever the frequency may be. It is shown in Art. 20 that if air is the dielectric the value of $\frac{1}{\sqrt{LC}}$, *i.e.* the velocity of the waves, is 3×10^{10} centimetres per second, which is equal to the velocity of light.

Now consider again the two equations—

$$i = i_1 \sin\omega\sqrt{LC}\,.\,x + i_2 \cos\omega\sqrt{LC}\cdot x$$
$$v = v_1 \sin\omega\sqrt{LC}\,.\,x + v_2 \cos\omega\sqrt{LC}\,.\,x.$$

Under certain conditions the reflected wave can be made equal to zero. If R is the value of the resistance at the receiving end, then if $R = \sqrt{\frac{L}{C}}$ it can be shown that all the energy is absorbed in this resistance, and none is reflected.

If there is no reflection, then :—

$$i = i_1 \sin\omega\sqrt{LC}\,.\,x,$$

and

$$v = v_1 \sin\omega\sqrt{LC}\,.\,x.$$

$$\therefore \frac{v}{i} = \frac{v_1}{i_1}.$$

Hence the ratio of voltage to current at any instant is the same all along the line, and is, therefore, equal to R, since $\frac{v_2}{i_2} = \mathrm{R}$. This applies to R.M.S. values of current and voltage, as well as to instantaneous values, but in addition the R.M.S. values are obviously constant whatever the value of x.

If a point distant 1 cm. from the transmitting end be taken, the current at this point will be $i_1 - jv_1\omega\mathrm{C}$, where v_1 is the voltage at the sending end, and the voltage will be $v_1 - j\omega\mathrm{L}i_1$, where i_1 is the current at the sending end at that instant. $j = \sqrt{-1}$, and denotes a phase difference of 90°.

Then
$$\frac{v_1}{i_1} = \frac{v_1 - j\omega\mathrm{L}i_1}{i_1 - jv_1\omega\mathrm{C}}.$$

$$\therefore \frac{v_1}{i_1} = \sqrt{\frac{\mathrm{L}}{\mathrm{C}}} = \frac{v_2}{i_2} = \mathrm{R}.$$

$$\therefore \mathrm{R} = \sqrt{\frac{\mathrm{L}}{\mathrm{C}}}.$$

184. Electromagnetic Waves in the Ether. (See Art. 21.)—It is stated in Art. 21 that Maxwell calculated that the velocity of electromagnetic waves through a medium is given by the expression:—

$$v = \frac{1}{\sqrt{\kappa\mu}} \text{ cm. per sec.},$$

where κ is the specific inductive capacity or dielectric constant of the medium and μ is its permeability. Theoretically and practically the value of this for electromagnetic waves (and light waves) in the ether has been found to be 3×10^{10} centimetres per second. A further simple treatment of this may be of interest to the reader.

The velocity of wave transmission in any medium is usually expressed by the relation:—

$$v = \sqrt{\frac{e}{d}}$$

where e denotes the modulus of elasticity involved, and d the density of the medium.

In order to find the values of e and d, which determine the velocity of transmission of electromagnetic waves, it is,

perhaps, simplest to compare the expressions for the energy per unit volume of a strained medium and the energy per unit volume of an electric field.

As a simple case consider a volume V of any medium to be compressed by hydrostatic pressure until the pressure per unit area increases from 0 to P, where P is very small, and let the change of volume be v. Then the *stress* is P and the strain is $s = v/\mathrm{V}$.

The work done in compression is $\frac{1}{2}\mathrm{P}v$, and if this work is stored up as strain energy in the medium, the potential energy so stored up *per unit volume* of the medium is $\frac{1}{2}\mathrm{P}v/\mathrm{V}$ or $\frac{1}{2}\mathrm{P}s$. The modulus of elasticity, the ratio of the stress to the strain, is given by $e = \mathrm{P}/s$, so that the energy of strain per unit volume of the medium is given by

$$\tfrac{1}{2}\mathrm{P}s \text{ or } \tfrac{1}{2}\,\frac{\mathrm{P}^2}{e} \text{ or } \tfrac{1}{2}es^2.$$

Now the energy per unit volume of an electric field can be shown to be expressed by $\dfrac{\mathrm{F}^2\kappa}{8\pi}$, F being the field intensity, and the value of F is given by $\mathrm{F} = \dfrac{4\pi\sigma}{\kappa}$, where σ is the density of the charge. Hence, combining these two expressions, we may express the energy per unit volume as

$$\tfrac{1}{2}\mathrm{F}\sigma \text{ or } \tfrac{1}{2}\mathrm{F}^2\,\frac{\kappa}{4\pi} \text{ or } \tfrac{1}{2}\cdot\frac{4\pi}{\kappa}\cdot\sigma^2.$$

If now F be taken to represent the stress in the electric field, and σ to represent the strain, then the three expressions just given correspond exactly with the three similar ones given higher up, and it will be seen that the electric elasticity is represented by $4\pi/\kappa$. The energy of an electric field has in this way been associated with potential energy of strain and the analogue of elasticity deduced.

In the same way, if the energy of a magnetic field be associated with the kinetic energy of a moving mass, the analogue of mass may be determined. In the case of a mass m moving with a velocity u, the kinetic energy $\frac{1}{2}mu^2$. Now the energy per unit volume in a magnetic field can be shown to be expressed by $\dfrac{\mathrm{H}^2\mu}{8\pi}$, and if we take the case of the field

inside an endless uniformly wound coil of n turns per unit length carrying a current I, the value of H is $4\pi n\mathrm{I}$, and the energy per unit volume is $2\pi(n\mathrm{I})^2\mu$ or $\frac{1}{2}.4\pi\mu(n\mathrm{I})^2$.

Now $n\mathrm{I}$ is the rate of displacement of electricity round unit length of the coil, and represents electrical velocity in the same way as σ represents electric strain or displacement. Hence, comparing $\frac{1}{2}.4\pi\mu(n\mathrm{I})^2$ with $\frac{1}{2}mv^2$, the quantity $4\pi\mu$ evidently corresponds to m and measures the electric mass or inertia per unit volume. That is, $4\pi\mu$ is the electric density of the medium.

The velocity of electric waves in a medium, for which $4\pi/\kappa$ is the electric elasticity, and $4\pi\mu$ the electric density, is evidently given by:—

$$v = \sqrt{\frac{4\pi}{\kappa} \Big/ 4\pi\mu},$$

$$\therefore\ v = \sqrt{\frac{1}{\kappa\mu}}.$$

For an exact and full mathematical investigation of the above, however, the reader should refer to Chapter XXII. of *Advanced Text-book of Magnetism and Electricity* by R. W. Hutchinson, M.Sc., A.M.I.E.E.

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